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Life cycle assessment (LCA) applied to the process industry: a review

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Abstract

Purpose: Life cycle assessment (LCA) methodology is a well-established analytical method to quantify environmental impacts, which has been mainly applied to products. However, recent literature would suggest that it has also the potential as an analysis and design tool for processes, and stresses that one of the biggest challenges of this decade in the field of process systems engineering (PSE) is the development of tools for environmental considerations.

Method: This article attempts to give an overview of the integration of LCA methodology in the context of industrial ecology (IE), and focuses on the use of this methodology for environmental considerations concerning process design and optimization.

Results: The review identifies that LCA is often used as a multi-objective optimization of processes: practitioners use LCA to obtain the inventory and inject the results into the optimization model. It also shows that most of the LCA studies undertaken on process analysis consider the unit processes as black boxes and build the inventory analysis on fixed operating conditions.

Conclusions: The article highlights the interest to better assimilate PSE tools with LCA methodology, in order to produce a more detailed analysis. This will allow optimizing the influence of process operating conditions on environmental impacts and including detailed environmental results into process industry.

Keywords

Life Cycle Assessment, Process Systems Engineering, Environmental Design and Optimization, Eco-Friendly processes, Industrial Ecology

Introduction

Since the beginning of the eighteenth century, the industrial society has grown up and spurred an increase in production of goods and services. Because the availability of raw materials is not unending and the ecosystem is not able to absorb infinite quantities of pollutants, environmental damages have risen. This has stimulated the birth of environmental policy (Eliceche et al. 2007), and thus the development of environmental assessment methodologies in order to lower the environmental footprints of product manufacturing (Jolliet et al. 2005; Telenko et al. 2008). This awareness of environmental concerns has led the manufacturing industry to become proactive in the design of new products, improve those which already exist and develop cleaner manufacturing processes (Harold and Ogunnaike 2000). Alongside this phenomenon, the concepts of "industrial ecology" (IE) and "design for environment" (DfE) have appeared. IE is defined as a "systems-based view of how, where and why environmental improvements can be made to develop a sustainable industry", which means "meeting the needs of current generations, without sacrificing the needs of the futures ones" (Anastas and Lankey 2000). Seager and Theis (2002) defined IE as "a field of study concerned with the inter relationships of human industrial systems and their environments". The notion of DfE is the "field of product design methodology that includes tools, methods and principles to help designers reduce environmental impacts". Both are general concepts where environmental tools are developed, especially life cycle assessment (LCA) which is considered as a well-established analytical method to quantify environmental impacts of a product, a service or a production process. During the early years of LCA, the methodology was mostly applied to products but recent literature suggests that it also has the potential as an analysis and design tool for processes (Burgess and Brennan 2001; Gillani et al. 2010). Simultaneously, in the field of process systems engineering (PSE), which deals with the design, operation, control and optimization of processes thanks to systematic computer-based methods, literature reveals the need to include environmental considerations in order to develop a more sustainable industry, and stresses the opportunity for adapting LCA methodology to PSE tools (Allen and Shonnard 2001; Grossmann et al. 2004; Grossmann and Westerberg 2000; Harold and Ogunnaike 2000).

This article will attempt to give an overview of the state of LCA methodology in the context of IE, and more precisely, to focus on LCA used as a methodology for environmental considerations affecting process design and optimization. The review will begin with a general description of the DfE principle and the opportunities regarding the integration of sustainability principles into PSE. Then the focus will shift to the interest of LCA, especially in the process industry. Lastly, the opportunities to integrate PSE tools with LCA methodology are highlighted. Actually this will allow producing more detailed analysis on the influence of process operating conditions on environmental impacts. The systematic integration of PSE tools into LCA for the environmental evaluation of industrial processes implies the need to adapt both LCA and PSE tools but will bring more comprehensive results.

1. Industrial Ecology and Process Systems Engineering

1.1. Design for environment: history and principles

During the second part of the twentieth century, the industrial sector became aware of the negative impacts generated by human activities. This induced reactivity and the development of new behaviours in order to avoid environmental damage. The first industries to come under scrutiny were the chemical processes and heavy industry sector, however this has tended to evolve to cover other sectors and different sizes of industry. The response of industry to mounting environmental pressure was progressive (**Figure 1**): it began with a "reactive period" (1970s) and crossed a "compliant period" (1970s-80s) before reaching a "proactive period" (1990s) with a real industrial response to environmental issues (Young et al. 1997). The most recent period is an "integrated and progressive period". Actually, a framework has been found thanks to the rapid evolution of DfE concept and its standardization into the ISO 14062 EMS (ISO 2003), which allows integrating environmental preoccupations from the early stages of the conception to the industrial production process. Moreover, the more and more widespread use of strong concepts ("industrial ecology", "eco-efficient manufacturing"), the development of some tools like green chemistry principles (Anastas and Warner 2000) and the generalization of LCA methodology show the progressive behaviour and the ambition of the process industry to improve their environmental footprint.

	Pre 1970s	1970s-80s	1990s	2000s
General Approach	**Reactive**	**Compliant**	**Proactive**	**Progressive**
Environmental Awareness	Very limited	Limited to particular manager or department	Heightened environmental awareness in all sectors and levels of organization	Environmental concerns are well-established in all sectors and levels of organization
Legislative Controls	Few regulations	Controls on emissions and waste	Integrated pollution control Product take-back legislation	More and more environmental policy Integrated product policy
Management Controls	Remediation	Inspection	Environmental standards and audits	Development of large concepts (Design for Environment, Eco-efficient manufacturing, Industrial ecology)
Pollution & Waste	Waste not an issue	End of pipe controls	Process innovation Life Cycle approach (LCA)	Generalization of LCA, development of integrated tools for environmental design and evaluation of industrial processes

Figure 1. Industrial response to environmental issues (inspired from Young et al. 1997)

DfE is a preventive approach, which involves the incorporation of environmental considerations into the design and optimization of products, processes and management systems at the early stages of conception, in order to minimize environmental impacts (Sroufe et al. 2001) and avoid having subsequent reduction measures (Gasafi et al. 2003). For example, in the chemical industry, DfE is apparent via development of "green" chemical routes, process intensification and process redesign (Bakshi and Fiksel 2003). According to Ernzer et al. (2003), most results end up in scientific publications rather than being transferred into practice, which implies that the number of design methods and tools used in the industry is relatively small compared to the number of existing ones. However, with the development of the EMS ISO 14062 standard (ISO 2003), which gives the general environmental integration principles and defines the effects on the environment to be considered during design and development stages, DfE principles are increasingly structured and have begun to be widely applied in various sectors.

It is difficult to draw up an exhaustive list of DfE tools. Moreover, it is a pity to restrict the analysis to the design of processes, because many other tools are conceived in order to improve these processes even when they are already developed, which is why in the following part, a description of the main environmental assessment techniques will be made, first on DfE, and then widened to assessment techniques in order to give a broader description and situate the application of LCA within it.

1.2. Environmental assessment techniques

Various assessment techniques can be applied, during the conceptual and embodiment design phases preceding LCA, when lack of time and detailed information prohibit a full LCA or simply when, for many reasons, it is just more suitable. One of the first examples quoted in the literature is the elaboration of *principles and guidelines* to guide designers (Ernzer et al. 2003). For example the twelve principles of *Green Chemistry*, were created in order to design chemical processes and products that reduce or eliminate the use and generation of hazardous substances. And Anastas and Lankey (2000) established a list of principles to prevent pollution during the life cycle step of chemical products or processes. However, these kinds of DfE principles have been developed by different designers in a large variety of industries (Hauschild et al. 2004), and the guidelines scattered throughout the literature are often focused on individual life cycle stages (design for recycling, design for energy efficiency…). Telenko et al. (2008) gives an overview of the different DfE principles, guidelines and checklists thus available. The aim was to synthesize them into comprehensive categories and hierarchical levels by developing an original methodology, and this resulted in the birth of 6 principles and 67 guidelines. However, if these guidelines often improved products, sometimes they were not well adapted to the context. For example, longevity of a product often means lower environmental impact, but if the product consumes large amounts of material or energy during its use, a short product life may be preferable. Hauschild et al. (2004) argued that an intuitive approach to DfE can fail to optimize overall environmental performance, which could be avoided by adopting a systematic, analytical approach and building a hierarchy of importance, which may explain why, in DfE methodologies, those which are more systematic and detailed are the most frequently adopted.

One of the most widespread methods is *multi-objective optimization* that consists of simultaneously optimizing two or more conflicting objectives (Alexander et al. 2000; Baratto et al. 2005; Dietz et al. 2006; Hermann et al. 2007). The initial idea was that it was impossible to satisfy simultaneously economic, social and environmental objectives, but possible to define a tradeoff between these objectives, thanks to a multi-objective optimization (Alexander et al. 2000).

Environmental risk assessment (ERA) is another interesting design tool for the improvement of existing processes. The general principle consists of estimating and evaluating risk to the environment caused by a particular activity or exposure (Burgess and Brennan 2001), and then developing risk management in order to reduce the risks of harmful effects to man and/or the environment (Olsen et al. 2001).

Cost-benefit analysis is a totally different approach relative to the “environmental economics” field, consisting of evaluating project quality by estimating its “real economic value”. This means taking into account the economic value of any loss or gain of environmental quality in the costs and benefits evaluation of a project. Thus, the total value of a project is obtained by summing all market and environmental costs and benefits (Pearce et al. 2006).

Environmental impact assessment (EIA) aims to predict and evaluate the environmental consequences of human activities, before they begin (Morgan 1998). This technique considers both environmental and socio-economic issues relative to a proposed project, usually by using checklists of potential environmental impacts, in order to provide qualitative and quantitative information, which then permits minimization of environmental impact and identification of benefits (Burgess and Brennan 2001). However, because this method focuses on a specific project (site specific, activity specific, and time specific), it is often more a legal procedure than a detailed environmental assessment tool (Jolliet et al. 2005).

At least, *life cycle assessment*, is the most well-known and powerful tool within DfE which will be described later. However, it appears that LCA is more reliable when coupled with other environmental approaches. In 2001, Olsen et al. produced a comparative study of LCA and ERA applied to chemicals that described the two methodologies and identified harmonies, discrepancies and relations between them. In the context of chemicals, the authors highlight differences between ERA, as an “absolute tool” able to predict the occurrence of adverse effects, and LCA, as a “comparative tool” used for environmental improvement of products. They also concluded that because they fulfil different purposes, both are necessary and cannot substitute for each other; they are complementary. Hermann et al. (2007) described an environmental assessment combining *LCA, multicriteria analysis, and environmental performance indicators*. The authors developed a new tool to perform an overall environmental assessment, involving solely the strengths of the three methods, releasing the user from their weaknesses: COMPLIMENT (COMbining environmental Performance indicators, LIfe cycle approach and Multi-criteria to assess the overall ENvironmental impacT). As well as applying this methodology to the specific case of eucalyptus pulp production in Thailand, the article gives an overview of studies that have combined several assessment tools. Recently, the coupling of exergy and environmental analysis in order to determine the environmental efficiency of the biological energy conversion process revealed the dependence between the thermodynamic parameters of the process, the operating conditions used and its environmental impacts (Buchgeister 2010).

1.3. Towards sustainable PSE?

Process systems engineering is a relatively young field of chemical engineering (about 35 years old), focusing on the design, operation, control and optimization of processes via the systematic aid of computer-based methods. This field “develops methods and tools that allow industry to meet its needs by tying science to engineering” (Grossmann et al. 2004), and encompasses a vast range of industries, such as petrochemical, mineral processing, advanced material, food, pharmaceutical and biotechnological. The significant accomplishments and the future challenges for PSE are summed up in **Table 1** (Bakshi and Fiksel 2003; Grossmann et al. 2004; Grossmann and Westerberg 2000). As well as these accomplishments and challenges, PSE has played an important role over the last decade by developing many useful concepts, tools and techniques for improving the viability of chemical processes, making them more and more industrially feasible (Grossmann et al. 2004), e.g. the use of statistical signal processing techniques in process operation, or the optimization and use of artificial intelligence methods in process design. In 2000, Grossman and Westerberg broadened the definition of PSE to “the improvement of decision-making processes for the creation and operation of the chemical supply chain. It deals with the discovery, design, manufacture and distribution of chemical products in the context of many conflicting goals”. This broadening to encompass the whole chemical supply chain (from the molecular to the company level) gradually led to the integration of safety and environmental factors as well as economics. Consequently, the emergence of environmental considerations and sustainability as a new industrial challenge give to PSE the opportunity to play an important role, by modifying the design and operation of existing processes, and then developing new products and technologies that are designed according to environmental considerations (Bakshi and

Fiksel 2003). In the same vein, Grossman et al. (2004) argued that environmental protection will become an important challenge for the process industry, which must be urgently and effectively addressed, because it has a profound effect on the long term viability and acceptance of the chemical industry. The author stressed that a stronger interaction between product and process design as part of LCA could be an interesting improvement.

Table 1. Accomplishments and future challenges in PSE (inspired from Grossmann and Westerberg 2000)

SIGNIFICANT ACCOMPLISHMENTS IN PSE IN THE PAST THREE DECADES	**FUTURES CHALLENGES FOR PSE**
Process Design Synthesis of energy recovery networks, distillation systems, reactor networks Hierarchical decomposition flowsheets Superstructure optimization Design multiproduct batch plants	*Process and Product Design* Design of new molecules Develop predictive capabilities for properties of compounds Process intensification **Design of sustainable and environmentally benign processes**
Process Control Model predictive control Controllability measures Robust control Non linear control Statistical Process Control Process Monitoring Thermodynamics-based control	*Process Control* Tight integration between design and control Integrate discrete events and safety functions in process control Improvement of sensors
Process Operation Scheduling of process networks Multiperiod planning and optimization Data reconciliation Real time optimization Flexibility measures Fault diagnosis	*R&D and Process Operations* Expansion of process operations: upstream to R&D and downstream to logistics and product distribution Process verification and synthesis of operation procedures Large scale continuous processes and small scale batch processes *Modeling* More flexible modeling environments Automating problem formulation through higher level physical descriptions
Supporting tools Sequential modular simulation Equation based process simulation AI/Expert systems Large scale Non linear programming Optimization of differential algebraic equations Mixed-integer nonlinear programming Global optimization	*Integration* Multiscale modeling Life cycle modeling *Supporting methods and tools* Large scale differential-algebraic methods for simulating systems on multiple scales Methods for simulating and optimizing under uncertainty Advanced optimization tools Improvement of tools for conceptual design Development of information modeling tools

2. Life Cycle assessment

2.1. Methodology for LCA

Life cycle assessment is a methodological framework for quantifying and analysing environmental impacts attributable to the life cycle of products, services and, more rarely, processes. Nowadays, this is a well-integrated tool in environmental management (Azapagic and Clift 1999), normalized by the ISO 14040-14044 (ISO 2006) environmental management system (EMS).

A full LCA would include a “cradle-to-grave” approach by considering each step of the life cycle: design/development of the product, raw material acquisition, manufacturing, distribution use/maintenance/re-use and end-of-life activities. The methodology is usually described under four different steps:

- **Goal and scope definition**: This step consists of drawing the studied system boundaries to ensure that no relevant part is omitted.

- **Inventory analysis**: Often based on a mass and energy balance, this step compiles and quantifies inputs (raw materials and energy) and outputs (wastes and others emissions) relative to the system throughout its life cycle. A review and comparison of life cycle inventory (LCI) methodologies was given by Suh et al. (2005), which identified six different methods and three hybrid approaches.
- **Impact assessment**: This step consists of aggregating and identifying the environmental burdens quantified in the inventory analysis, into environmental impact categories (Azapagic and Clift 1999) such as climate change, stratospheric ozone depletion, tropospheric ozone creation (smog), eutrophication, acidification, toxicological stress on human health and ecosystems, resource depletion, water use, land use, noise and others. Moving from inventory to impact assessment is one of the most difficult steps of LCA, largely discussed in the literature and implying many inconsistencies between LCA practitioners. Even if Owens (1997) had already observed this before, it is still one of the main limits voiced concerning LCA methodology, and is why different methodologies have been developed for life cycle impact assessment (LCIA) over the last decade: EDIP97, Eco-indicator 99, CML 2001 (Dreyer et al. 2003), IMPACT 2002+ (Jolliet et al. 2003), etc.
- **Interpretation**: This last part allows conclusions to be drawn concerning environmental damages generated by the system, using results provided by the impact assessment step.

LCA methodology and limitations have been widely described and improved over the last three decades, and are covered in many articles (Ayres 1995; Guinée et al. 2011; Thorn et al. 2011). Rebitzer and Pennington (2004) provided a well-detailed two-part methodology review, covering the framework, goal and scope definition, inventory analysis and application in the first part and current impact assessment practice in the second (Pennington et al. 2004; Rebitzer et al. 2004). Recently, Finnveden et al. (2009) published a review dealing with recent developments in LCA methodology. This article focused on areas with significant methodological development such as definition of attributional and consequential analysis, system boundaries and the improvement of allocation rules, the development of new inventory databases, current developments in LCIA and lastly improvements made regarding consideration of uncertainties. Concerning consequential LCA, which represents the convergence between LCA and economic modelling methods, research and applications are in their infancy although a very detailed review has been made by Earles et al. (2009), where the authors have covered the historical development of this particular methodology, plus previous literature on the topic, bringing an interesting perspective to this new methodological approach.

2.2. Historical review of LCA methodology

Azapagic (1999) and Burgess et al. (2001) provided a brief history of the methodology from its original form (‘net energy analysis studies’ 1970), to its slow evolution (the consideration of waste and emissions), and then the creation in 1993 of a general method for conducting effective LCA studies by the Society for Environmental Toxicology and Chemistry (SETAC 1993). They also described and discussed aspects of the ISO standard (ISO 1997) and stressed the specificity of including a sensitive analysis for this latter.

Young et al. (1997) proposed a chronological study of the industrial response to environmental preoccupations, and more recently, Guinée et al. (2011) provided an article dealing with a detailed history of LCA methodology and its probable evolution in the years to come, totally in line with the previous work. This article describes how LCA, which was basically a tool for evaluating environmental impact, was integrated and promoted by governments all around the world as the core element of their environmental policy. The authors present an original point of view and divide the last four decades into three main categories:

- *1970-1990 is named ‘the decade of conception’*, because widely diverging approaches, terminologies and results were developed during this period. This can be explained by a clear lack of international communication concerning the methodology employed. The evolution between 1970 and 1990 as a reactive period moving to a compliant period explains the discrepancy in methodology by the fact that it takes time to become aware of environmental aspects (Young et al. 1997).
- *1990-2000 is, for the authors, the ‘decade of standardization’*. The period 1970-1990 was one where the drawbacks in the methodology were identified and a more common theoretical framework developed. The 1990s was a proactive period during which the SETAC coordination and the ISO standardization converged on the different framework developed. However, the ISO never provided a detailed standardization because “there is no single method for concluding LCA”.
- *The period 2000-2010,* according to Guinnée et al. (2011) is the ‘*decade of elaboration*’. LCA was becoming a generalized tool for environmental assessment, but new divergences in methodologies appeared. Because the ISO standardization was very wide and did not aim to develop the methodology in detail, many studies have been performed within the spirit of LCA methodology, but with differences regarding methodological approach. To deal with this problem, a new LCA textbook was published during this decade (European Commission 2010; Guinée et al. 2002; Jolliet et al. 2005), and an effort was made to harmonize and update LCI data via the development of the Ecoinvent database, which made available more than 2,500 product and service LCIs (Frischknecht et al. 2005). Very recently, the UNEP/SETAC provide a guide which aims to give good practices for improving generation, compilation and accessibility of LCA data, and develop the interlinkages between worldwide databases (UNEP and SETAC 2011).

2.3. LCA application fields

At the end of the twentieth century, the adoption by industry of the LCA approach was recognized as relatively slow, but the methodology was progressively gaining acceptance. Some sectors such as plastics, detergents, personal care products and automobiles were identified as pioneers investing in LCA. They were closely followed by agriculture, mining and oil and gas extraction, the construction/building material sector, manufacturing industries and retailing, and more recently by infrastructure industries (electricity, gas and water supply, transport, storage and communication). This methodology was also considered as one of the best tools for developing integrated and efficient environmental policies (Berkhout and Howes 1997). There are many areas in which LCA can be applied: in the macro-scale analyses sector as well as in micro-scale areas, in the public sector as well as in individual organizations, in ecodesign and in product engineering... Currently, in the industrial sector, the approach is largely applied to biofuels (Lim and Lee 2011; Ndong et al. 2009; Neupane et al. 2010; Renó et al. 2011; Singh and Olsen 2011), energy (Finnveden et al. 2005; Pehnt 2006), waste and water treatment (Fuchs et al. 2011; Sablayrolles et al. 2010) and other industries (Awuah-Offei and Adekpedjou 2011; Ortiz et al. 2009; Pehnt and Henkel 2009). LCA could also be used in EMS, as a tool for identifying the significant environmental aspects of products and services in an organization engaged in the ISO 14001 standardization process (Lewandowska 2011).

LCA can be used with several aims, at different stages of a product life cycle (Keoleian 1993). The methodology was traditionally used to understand three types of problem: assessment of single products to learn about their environmental impacts, comparison of process routes in the production of substitutable products or processes, and comparison of alternative ways for delivering a given function (Berkhout and Howes 1997). More recently, it was similarly argued that

LCA is mainly used to compare different products, processes and activities delivering similar functions, but this methodology can also be used as a standalone tool to identify hotspots in a life cycle (Gasafi et al. 2003).

A new approach for LCA is to focus on the product conception in order to build eco-friendly processes. This approach can lead to detailed analyses of processes and to the development of process specific LCA methodology, confirming that the indisputable opportunity for LCA is in the field of PSE, already discussed in the first part of this review. As Grossman et al. (2004) argued, "global LCA is a major research challenge in the PSE area over the next decade".

3. LCA and process design: state of the art and challenges

The two previous sections of this paper have argued that DfE contains efficient tools, which have become more and more useful in our industrial and environmentally open-minded society. Moreover, the interest of LCA has been proved: a powerful tool, gaining in complexity and in maturity and increasingly accepted as a valuable methodology for a large field of applications. However, it is clear from the literature that the applications of LCA to industrial process analysis are not widespread, but becoming more and more important through the building of new integrated methodology. The following part deals especially with this aspect.

3.1. Interest of an application in process design and optimization

Most of the initial life cycle studies published compared product alternatives, and it was rare to find studies dealing with process design in the early stages of the methodology (Burgess and Brennan 2001). A detailed treatment of the application of LCA to process selection, design and optimization was published (Azapagic 1999), and since this early review, methodological aspects of LCA have been improved and the methodology is more and more accepted within the scientific community. The starting point for the use of LCA for sustainable development has been the design of "environmentally friendly" products, and this approach was progressively extended to the process industry (Young et al. 1997). Basically, the methodology was mainly applied to products, by developing the "from cradle-to-grave" approach to the life cycle (as described in the previous section), targeting just the product because the process, from this point of view, is considered as a part of the product life cycle (manufacturing the product). However, today, its application to process assessment is increasing. Little by little, works are appearing in the literature that develop another perception of life cycle and process. In fact, the process could also be seen with its own life cycle: design of the process (planning, design, R&D), installation, use of the process (manufacture of the product), disassembly of the process and remediation of the used lands (Allen and Shonnard 2001). **Figure 2** illustrates the different LCA approaches that could be adopted and the main alternative uses of LCA to products, and LCA to processes.

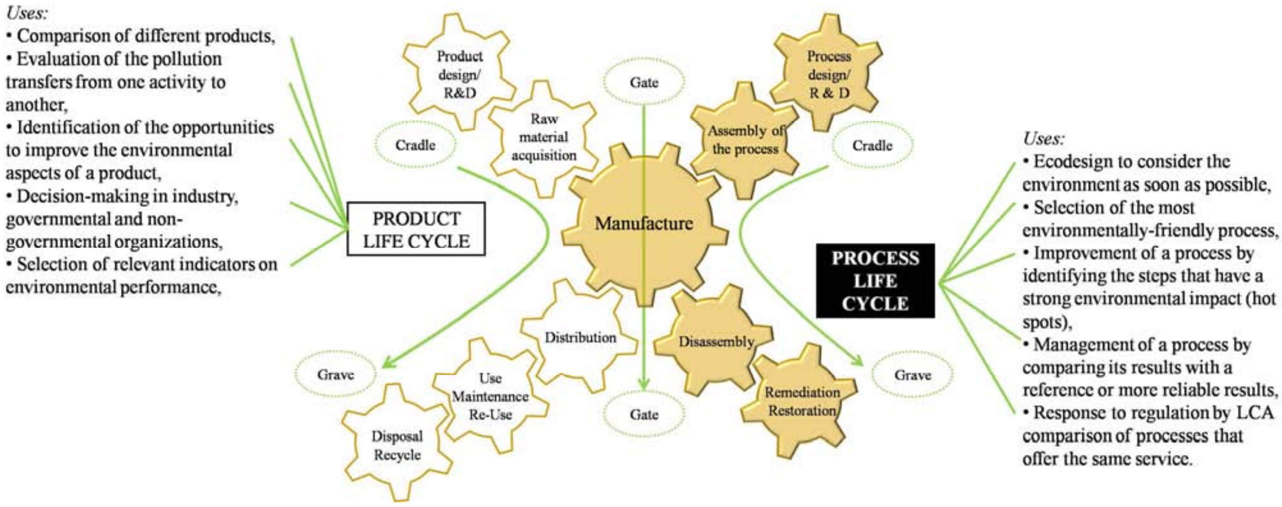

Figure 2. Illustration of different life cycle approaches (inspired from Allen and Shonnard 2001; Chevalier et al. 2003)

LCA applied to process can also adopt a “cradle-to-gate” approach, which means that the study stops at the gate of the factory: the manufacturing product end of life of is not considered. For example, Serres et al. (2011) presented a detailed study on a direct additive laser manufacturing process, which allows the direct manufacturing of small parts with complex shapes, giving equivalent properties as conventional machining or casting techniques. They built their study on the fabrication of a selected titanium pieces, and this allows comparing this new process with a more classical one (machining), showing the environmental benefice of the laser manufacturing process. Moreover, another approach has been developed, which considers the process from “gate-to-gate”, meaning that the system boundaries of the LCA end at the manufacture gate and do not consider the whole life cycle. This approach is rarely used but finds an application in chemical engineering process design, when factual or literature information is unavailable for a study (Jiménez-Gonzalez et al. 2000). For example, Portha et al. (2010) studied a naphtha catalytic reforming process, by considering only the heat production and distribution and the tree main steps of the process (reaction, separation and catalyst regeneration). The gate-to-gate approach, combined with process simulation, helped the authors to study the influence of temperature on environmental impacts.

Thus, regarding the process industry, it was suggested that LCA could be used in various contexts as for example “the use at the research and development phase of a process, in guiding process evolution; in process design for comparison and selection of options; in business planning for identifying weak links in a processing chain or in comparing processes with those of business competitors” (Burgess and Brennan 2001). Thus specialists’ recent interest in the application of LCA to processes would seem obvious, and actually the technique could represent an efficient tool for the design and improvement of processes, by taking into account classical criteria like yield and cost concerns, and incorporating LCA-derived environmental considerations.

3.2. LCA applied to processes: state-of-the-art and future perspectives

3.2.1. Pre 2000 studies

One of the first works dealing with LCA applied to process application is attributed to Furuholt (1995), comparing the production and use of different petrochemical products. The originality of this study is that instead of considering the refinery step as an unknown and nondetailed process (as a black box, with just input and output known), the author divided it into several subunits and tried to quantify the energy demand and emission of pollutants relative to these subunits. At the same time, Stefanis et al. (1995) were working on the minimization of environmental impacts of vinyl chloride monomers from ethylene production process, and were considering the opportunity of applying LCA as a tool for process optimization. In 1996, Kniel et al. (1996) linked LCA to an economic analysis, in order to achieve a multi-objective analysis for the optimization of a nitric acid plant, and this study is one of the first where the aim of using LCA as a tool for process design and optimization is clearly displayed. The paper concluded that it was possible to outline a best solution thanks to this technique and stressed the multiple ramifications and improvements possible via the methodology. The authors asserted that LCA is one of the best methodologies able to link unit processes, environmental impact and economic aspects of processes. Using the same multi-objective approach, Mann et al. (1996) combined LCA and economic studies on a biomass gasification energy production process.

One of the most relevant authors on the "LCA and process application" topic was obviously A. Azapagic. She wrote a very detailed review on the application of LCA in process selection, design and optimization, as a tool for identifying clean technologies, and published several works on LCA and multi-objective optimization of processes (Azapagic 1999; Azapagic and Clift 1999).

3.2.2. LCA and processes: the current state-of-the-art

Since 2000, the field of *multi-objective optimization* has been largely completed (**Table 2**). Alexander et al. (2000) developed an environmental economic multi-objective optimization on a nitric acid plant study, where they used LCA to obtain the environmental impact information, which was then used to define environmental objectives to introduce into the optimization algorithm. More recently, LCA was used by Dietz et al. (2006) to obtain a pollution index, which was then included as input environmental data for solving a cost/environment multi-objective system. Similarly, environmental life cycle impacts have been used as a tool for process optimization in a utility plant by Eliceche et al. (2007).

However, the incorporation of LCA in multi-objective optimization was not the only use to be under the scrutiny of process design and analysis practitioners. For example, some works in the literature use *LCA combined with other tools*. In the field of supercritical water gasification, Gasafi et al. (2003) presented one application of LCA in an early phase of process design. They adopted an original approach that consisted of coupling LCA with a hierarchical approach to quantify environmental impact throughout the process chain, and identify the environmental damage "hotspots" which were then focused on for optimization of environmental performance. Recently, Da Silva et al. (2009) worked on an integrated methodology to analyse a generic production process, considering both environmental impacts and related costs. They applied the methodology to an example of incinerator production and combined different existing methodologies like LCA, activity-based costing, environmental management accounting, economic model for control and evaluation of environmental impacts and risk matrix. Hermann et al. (2007), quoted earlier for their work, applied the COMPLIMENT tool to the case study of eucalyptus pulp production using soda treatment and chlorine bleaching processes. The interesting point of this work was that it was run at two different levels: large system boundaries (cradle-to-grave approach: from the eucalyptus plantation to the finished product) and at a process level (gate-to-gate approach: considering all the processes connected to the soda pulping production of eucalyptus, and also the on-site processes (waste treatment, chemical recovery, etc.)).

Table 2 Application fields and characteristics of studies dealing with LCA and processes since 2000

Source	Application Field and scale	Design or existing process?	Approach	Data collection	PSE and LCA
Alexander et al. (2000)	Nitric acid plant Plant scale	Design	Multi-objective optimization Cradle to gate	Use of HYSYS™ to obtain LCA inventory data	LCA → Optimization model PSE → LCA
Baratto et al. (2005)	Auxiliary power units	Existing	Multi-objective optimization Cradle to grave	Use of ASPEN to obtain LCA inventory data	PSE → LCA
Dietz et al. (2006)	Multiproduct (proteins) production process Process scale production	Design	Multi-objectives optimization Gate to gate	Use of LCA results in the optimization	LCA → Optimization model
Eliceche et al. (2007)	Ethylene process Plant scale	Existing	Multi-objectives optimization		LCA → Optimization model
Gasafi et al. (2004)	Treatment of organic feedstock (supercritical water gasification)	Design	Assessment of the process by coupling LCA and hierarchical approach Identification of the main sources of environmental impacts Cradle to gate	Laboratory tests Literature data Assumptions	No
Hermann et al. (2007)	Eucalyptus pulp production using soda production process Large-scale production	Existing	Analysing a process by combining several environmental assessment tools Cradle to grave and gate to gate	Literature data Black box	No
Da silva et al. (2009)	Metallurgical industry Industrial scale	Existing	Simultaneously evaluate environmental impacts and costs	Literature and industrial data	No
Chevalier et al. (2003)	Flue gas cleaning processes Plant treatment scale and emerging process scale	Existing and emerging	Environmental diagnosis of an emerging process Comparison of two different processes	Literature data Unit process = black box	No
Koroneos et al. (2004)	Hydrogen production processes Industrial scale	Existing	Assessment and comparison of processes Cradle to gate	Literature data Unit process = black box	No
Norgate et al. (2007)	Metal production processes Industrial scale	Existing	Assessment and comparison of processes Cradle to grave	Literature data Unit process = black box	No
Benko et al. (2007)	Gas desulphurization processes Plant scale treatment	Existing	Assessment and comparison of processes Gate to gate	Literature data Unit process = black box	No
Scipioni et al. (2009)	Municipal solid waste incineration processes Plant scale treatment	Design	Comparison of different design solutions Identification of hotspots Cradle to gate	Data collection at subunit process scale Field and literature data	No
Kenthorai Raman et al. (2011)	Biodiesel production processes Process scale production	Existing	Comparison of three different processes Cradle to gate	Databases and literature Take a "snapshot" of dynamic processes → black box	No
Brentner et al. (2011)	Industrial production of algal biodiesel Process scale production	Existing and under development	Comparison of several processes Cradle to gate	Literature and industrial data	No
Tangsubkul et al. (2006)	Microfiltration process Unit process scale	Existing	Unit process analysis Cradle to grave	Experimental, literature and industrial data	No
Portha et al. (2010)	Naphtha catalytic reforming process Process scale treatment	Existing and design → improvement	Comparison of two different processes Unit process analysis Cradle to gate and gate to gate	Use of process simulator (Pro II 8.0) to obtain LCA inventory data	PSE → LCA
Kikuchi et al. (2010)	Biomass-derived resin Unit process scale	Design	Process analysis Cradle to grave	Use of Aspen Plus™ and Aspen HYSYS™ to obtain LCA inventory data	PSE → LCA
Gerber et al. (2011)	Energy conversion systems	Design	Process systems design thanks to the integration of LCA into thermo-economic models Cradle to gate	Process flowsheet model LCI database	PSE ↔ LCA

Another common utilization of LCA on processes that stood out in this advancement review was that of *comparing different scenarios* (existing or under design). Brentner et al. (2011) presented an LCA that compared various methods for a sustainable, full-scale production of algae biodiesel. The innovation is inherent to the fact that a number of technology options were considered for each process stage, and different technology combinations were assessed to identify the most preferable process. The authors also aimed to identify design parameters that collectively indicated the most potentially sustainable system. Still in the field of biodiesel, Kenthorai Raman et al. (2011) developed a cradle-to-gate approach to analyse three different catalytic processes. Concerning gas treatment, Benko et al. (2007) proposed a comparison of flue gas desulphurization processes based on a classical LCA, and Scipioni et al. (2009) developed a study, interesting in that it concerned an incineration plant under design, and analysed different scenarios in order to choose from several design solutions. The authors then outlined the opportunities for detecting 'priority' points (hotspots) where it was possible to intervene to develop the most technologically advanced solution. Other fields were also investigated with such approach for the comparison of municipal solid waste incineration (Chevalier et al. 2003) for hydrogen fuel production (Koroneos et al. 2004) and for metal production processes (Norgate et al. 2007).

Lastly, another interesting point that could be treated by LCA is *the selection of operating conditions for a unit process*. Such studies are quite rare, but some exist in the field of a microfiltration process (Tangsubkul et al. 2006), in the Naphtha catalytic reforming process (Portha et al. 2010), in the biomass-derived resin production process (Kikuchi et al. 2010) and in the assessment of an energy conversion system (Gerber et al. 2011).

3.2.3. PSE tools/LCA methodology coupling: future perspectives?

The previous section has given an overview of the different studies made over the last two decades, concerning LCA applied to process design and optimization. It allows us to conclude that there are three ways of applying LCA to the process issue:

- multi-objective optimization where LCA is used for inventory data and the result of the assessment is injected into the optimization model (Dietz et al. 2006; Eliceche et al. 2007; Gerber et al. 2011);
- coupling LCA with other assessment tools to complete the studies and improve the limitations of the LCA and
- analyzing environmental impact of processes by using the LCA methodology alone, in order to compare different scenarios, or for identifying the hotspots.

Nevertheless this latter option often sees processes as black boxes and constructs LCIs using the literature or industrial data at fixed operating conditions, without taking into account operating parameter variations (Benko and Mizsey 2007; Brentner et al. 2011; Gasafi et al. 2003; Kenthorai Raman et al. 2011; Koroneos et al. 2004; Norgate et al. 2007; Scipioni et al. 2009). This approach is of interest when the aim is to assess the process via an overall approach or to compare different processes in their global nature, but it is limiting when dealing with analysing each process unit as a complex system, and determining what are the best operating conditions. However, in the last few years, some authors have become aware of this problem and point out the opportunity to incorporate LCA into the PSE approach for process design and analysis (Alexander et al. 2000). At the same time, they pointed out that because of the difficulty of translating process information into environmental objectives, incorporating environmental sensitivity into the PSE approach was unsatisfactory. They proposed a multi-objective optimization in the PSE approach and used LCA linked with process simulation tools (Hysys) to identify the environmental objectives: an illustration of the advantage of injecting PSE results into LCA. Some years later, Chevalier et al. (2003) demonstrated how to develop collaboration between the LCA approach and chemical engineering, in order to make process inventory data more accurate and test other process configurations, thus improving knowledge of unit processes.

In their very detailed work on microfiltration process assessment, Tangsubkul et al. (2006) have in turn demonstrated how to determine optimal operating conditions for a membrane unit process, from an environmental perspective. They did not use any modelling software for the process simulation and the study was quite laborious and obviously could not be applied as a generalized application in the process industry, but they have shown the interest of such an approach.

The integration of operating conditions was sometimes achieved in part by using mass transfer models and by introducing modelling tools upstream of the LCA (Baratto and Diwekar 2005). And very recently in the oil and gas industry field, Portha et al. (2010) applied LCA to the naphtha catalytic reforming process. Process simulation tools were used with LCA in order to study the influence of operating parameters on environmental impacts, by performing a comparative study on two processes, studying the influence of furnace inlet temperature and the influence of feed on this impact. Very recently, estimating missing data using process simulation was done in a case study dealing with the design of a process for the production of biomass-derived polypropylene (Kikuchi et al. 2010). The authors presented a framework integrating computer-aided process engineering and LCA. In the field of energy production from lignocellulosic biomass, a flowsheeting model, providing material and energy flows and equipment sizes, was exploited to calculate the LCI of emissions and extraction flows associated with the process equipment and its operation (Gerber et al. 2011). The aim is then to propose a systematic approach for integrating LCA in process systems design using multi-objective optimization, which allows the simultaneous consideration of the influence of the process design and its integration, on the thermodynamic, economic and environmental life cycle performance in the early stages of the conceptual process synthesis.

These latter studies and their recentness testify to the fact that recognition of the operating parameters injected into LCA applied to processes is very important, and thus imply that the coupling between LCA and PSE, illustrated in **Figure 3**, is a future challenge for LCA when applied to the process industry.

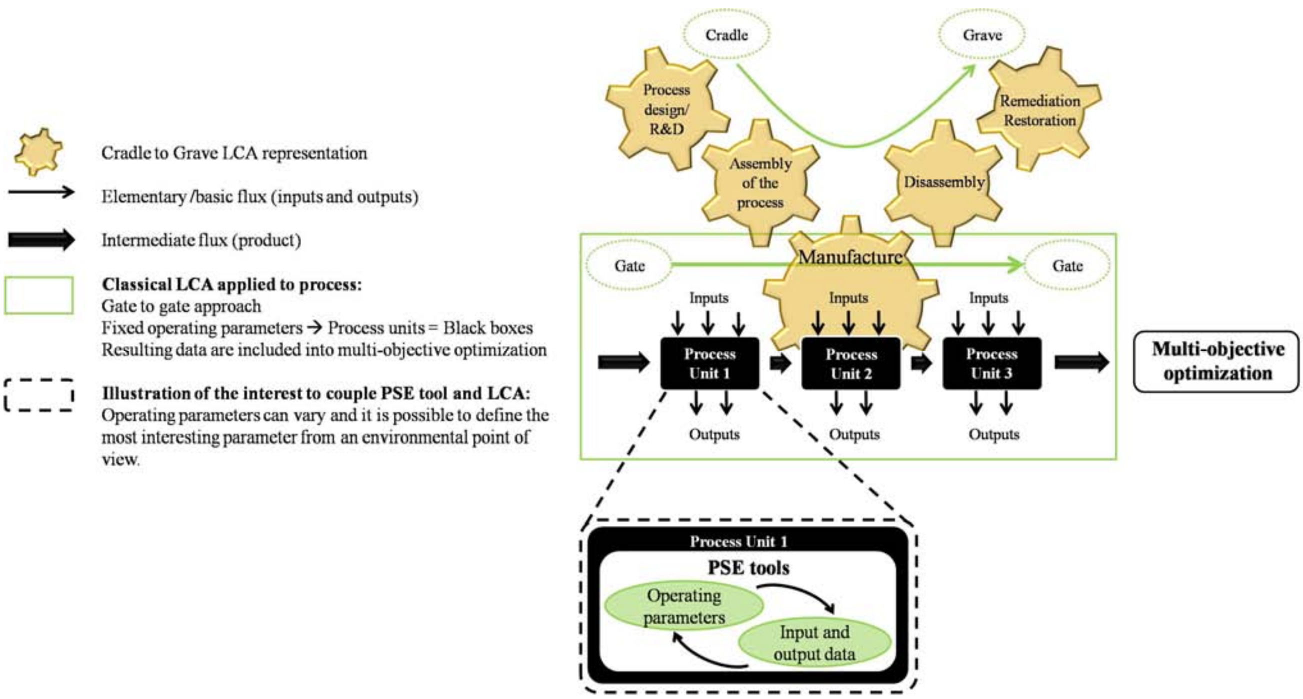

Figure 3. Illustration of PSE tool integration into LCA methodology for process

Conclusion

Over the three last decades, LCA has been identified as one of the most interesting tools for environmental assessment. Its current wide use denotes that since its first application, the methodology appears to have evolved from a very specific tool for product assessment to a far ranging one, with an application to products, services, EMS, environmental policies, processes, as a standalone tool or combined with other environmental assessment tools. At the same time, the interest in the tools developed for the design of new processes and the improvement of older ones (PSE tools) has risen significantly.

This literature review has highlighted the fact that the use of LCA on processes has taken time to develop; but in the last few years, this field of application has been much under the spotlight and so today, studies on LCA applied to process analysis are readily available. In addition, LCA is often used to obtain input data for multi-objective optimization of processes. However, the coupling between LCA and PSE tools must be improved, notably to produce more detailed analysis on the influence of process operating conditions on environmental impacts. The systematic integration of PSE tools into the elaboration of environmental assessment of processes will bring scientific legitimacy to environmental evaluation by LCA.

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