Journal of Cleaner Production 90 (2015) 128–141

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Roadmap for Environmental Impact Retrofit in chemical processes through the application of Life Cycle Assessment methods

Ana Filipa Mimoso [a], Ana Carvalho [b,*], Acácio Nobre Mendes [a], Henrique A. Matos [a]

[a] CERENA, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] CEG-IST, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 8 July 2014
Received in revised form
3 November 2014
Accepted 18 November 2014
Available online 25 November 2014

Keywords:
Environmental impact
Life Cycle Assessment (LCA)
Life Cycle Impact Assessment (LCIA) methods
Chemical processes
Framework
SimaPro

ABSTRACT

The European Commission presented the Life Cycle Assessment as the best framework for evaluating the environmental impact of products/processes. Companies are trying to reduce the environmental impact of products/processes, therefore the European Commission underlined the need for guidelines that select the most relevant impact categories depending on the type of product/process analysed. This work aims to propose a new framework called Roadmap for Environmental Impact Retrofit, which assesses different retrofit design alternatives of a given chemical process, through the application of Life Cycle Impact Assessment methods, and identifies a path for possible environmental impact improvements based on the identification of the most critical impact categories. The framework has been applied to the acetone-chloroform separation process as an illustrative case study. The framework has proved to be an efficient tool to assess different design alternatives in chemical processes in terms of environmental impacts. From the application of the framework, it was possible to conclude that future retrofit actions should primarily focus on some critical impact categories. The most important impact categories are identified by the Pareto principle. The framework allows practitioners to assess retrofit designs in terms of their environmental impact improvements and guides them in the elaboration of a new retrofit action plan, which will give priority to the most critical environmental impact categories. Therefore the framework represents a first step towards the European Commission goals.

1. Introduction

In 1987, the concept of sustainable development became widely known through the publication of the Brundtland Report (WCED, 1987). Since then, and particularly in the last two decades, scientific community has made efforts to conceive tools that help consumers, policy makers and business companies to assess the environmental, social and economic impacts of their actions.

Together with the economic and social pillars of sustainability, environmental sustainability plays a key role in the reinforcement of international competitiveness and resource efficiency (Costantini and Mazzanti, 2012). The number of scientific publications in the environmental assessment area has been increasing in the past decades, showing the increasing concerns of the society regarding this key aspect (Carvalho et al., 2014). It also confirms that scientific community has been actively seeking for comprehension regarding the study and quantification of environmental impacts. The European Commission has pointed out the importance of the LCA framework in this field and has shown its interest in the standardisation of the already developed methods (European Commission, 2014).

LCA quantifies energy and materials used, wastes released to the environment and performs the impact assessment of those inputs and outputs (Miettinen and Hamalainen, 1997). The application of LCA follows a specific procedure that is defined and described in ISO 14040 (2006) and ISO 14044 (2006). The quantification of the impact in a LCA context is achieved by the application of Life Cycle Impact Assessment (LCIA) methods. In the last two decades, many authors proposed different LCIA methods. Carvalho et al. (2014) have systematised 25 methods to assess environmental impact of industrial chemical processes and have identified 13 of them as being specifically conceived to be applied in LCA context. This number clearly illustrates the considerable amount of methods currently available in the literature. Moreover, the methods are not standardised since they consider different impact categories and nomenclatures, which reinforces the concerns shown by the

* Corresponding author.
E-mail address: anacarvalho@ist.utl.pt (A. Carvalho).

http://dx.doi.org/10.1016/j.jclepro.2014.11.057

European Commission (Carvalho et al., 2014). UNEP/SETAC Life Cycle Initiative has put efforts in bringing global guidance on environmental LCIA indicators and methodologies behind these indicators. This initiative will enter on its third phase, which strategy will be implemented based on the outcomes of a workshop "Life Cycle Impact Assessment (LCIA) – where we are, trends, and next steps" (Rack et al., 2013). Efforts have also been made by scientific community in order to identify the best characterisation models considered in many different LCIA methods and to provide recommendations to LCA users (Hauschild et al., 2013).

The LCIA methods have become common tools for the decision making process, in the evaluation of industrial processes. For example Boltic et al. (2013) applied LCIA methods to assess the pharmaceutical processes. Jia et al. (2014) assessed the production of the vanadium extraction industry through the application of LCIA methods. Yilmaz et al. (2014) applied LCA as a decision support tool for evaluation of best available techniques for cleaner production of iron casting. However, when different LCIA methods are applied to a given process/product, different results and conclusions can be achieved. Several authors have attempted to compare the influence of LCIA methods in the assessment of products and processes.

Renou et al. (2008) applied CML 2000, EI 99, EDIP 96, EPS and Eco-points 97 to the study of a full-scale wastewater treatment plant. For specific categories, namely greenhouse effect, resources depletion and acidification, the authors have reported a consistent assessment between the LCIA methods. However, for human toxicity, large discrepancies were found between the different methods.

Pizzol et al. (2011a) conducted a detailed study on the impact of metals' emissions on human health, by using Stepwise 2006, IMPACT 2002+, EDIP 2003, EI 99, CML 2001, TRACI 2, ReCiPe, EPS 2000 and USEtox. They found out a poor or no agreement between the methods, reporting great changes on the relative contribution of each metal and on the different metals' contribution for the total impact on human health. The discrepancies are mainly attributed to the different number of metals included in each method, as well as the techniques considered in the calculation of the characterisation factors. The authors suggest USEtox as recommended best model for LCIA human toxicity since, despite the high uncertainties regarding metals, there is a large consensus behind it. The same authors also performed a similar study to the previously described, but focused on the eco-toxicological impact instead of human health (Pizzol et al., 2011b). Again for this study, they concluded that there is a poor agreement between methods in the determination of the total impact attributable to metals, as well as in identifying which metal is responsible for the highest impact. The authors present suggestions to guide in the choice of the proper, case-specific, LCIA method.

Buchgeister (2012) applied EI 99, CML 2001, IMPACT 2002+ to a thermochemical process for the conversion of biomass to electricity. They concluded that, for all methods, the highest contributions for the total environmental impact come from the same input streams and system components. However, depending on the LCIA method considered, different chemical pollutants are responsible for the highest environmental impact. As a consequence, the authors recommend the use of more than one LCIA method in order to obtain more information in detail about the environmental pollutants.

Cavalett et al. (2013) used *SimaPro* software to apply CML 2001, IMPACT 2002+, EDIP 2003, EI 99, TRACI 2, ReCiPe and Ecological Scarcity 2006 to compare the environmental impact associated to the use of gasoline and ethanol from sugarcane as liquid fuel for transportation in Brazil. They reported the existence of a relative agreement on the results obtained by the different LCIA methods regarding the equivalent environmental impact categories at midpoint level. However, the single-score results are different for the methods considered.

The work developed by the previous authors considers an environmental assessment of a given process or product. The authors concluded that LCIA methods are not standardised and verified that different impact categories are assessed when applying different methods. However, none of the previous authors have suggested a guideline that helps decision-makers to deal with these non-standardised results. It still lacks a framework that deals with this wide information and that guides decision-makers on the selection of LCIA methods when assessing different design alternatives of a given process. Moreover, it is still missing information on how to select impact categories for further improvements in products/processes. It is crucial to be able to extract the most from the methods, namely information about the impact categories that should be firstly improved so that environmental impact of products/processes can be effectively reduced. These literature gaps led to two main research questions:

RQ1 – How should different LCIA methods, be used in order to assess different design alternatives for a given process?
RQ2 – How can different LCIA methods be used in order to define a new plan regarding retrofit actions?

This work aims to answer these questions by presenting a new framework for process retrofit design and assessment. The framework has been applied to a case study of acetone-chloroform (trichloromethane) separation (Mendes et al., 2011) in order to illustrate its application. This case study presents two design alternatives: a base case and a new design alternative obtained from the base case by process retrofitting. This last one is considered more sustainable than the former, based on the analysis of the IChemE sustainability metrics (Azapagic et al., 2002).

2. Framework

The proposed framework involves the application of different methods to assess different design alternatives for a given process. The LCIA methods used in the framework are explained in Section 2.1 and a description of the assumptions considered in the framework is presented in Section 2.2. The framework is described in Section 2.3.

2.1. Selection of LCIA methods

The proposed framework is intended to guide decision-makers in the application of a diversity of LCIA methods, taking advantage of the different information obtained by their applications. This means that the framework does not intend to identify the best method to be used, but instead it intends to take advantage of the different methods' data and guides the decision-makers in their analyses, depending on the case study that is being analysed. In this work some methods are pointed out as appropriate methods to conduct this type of analysis, however other methods can be included in the analysis upon decision maker's choice.

Carvalho et al. (2014) presented a literature review including 25 methods for environmental impact assessment in chemical processes. Some of these methods cover several impact categories (*e.g.* ReCiPe, Eco-Indicator 99, *etc.*) but others were developed to address only a specific issue (*e.g.* USEtox exclusively dedicated to ecological and human toxicity). Carvalho et al. (2014) identified 13 methods as being specifically conceived to be applied in LCA context, or in other words covering several impact categories, which is the aim of this work.