# INTEGRATED LIFE CYCLE ANALYSIS APPROACHES TO STRATEGIC DECISION MAKING IN WASTE TO ENERGY

## PhD Thesis

*Answers to Review of Prof. Dr. Petr Stehlik*


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| The environmental bill of material and technology routing: an integrated LCA approach<br>L De Benedetto, J Klemeš<br>Clean Technologies and Environmental Policy 12 (2), 191-196 | 14 | 2010 |
| LCA as environmental assessment tool in waste to energy and contribution to occupational health and safety<br>L De Benedetto, J Klemeš<br>CHEMICAL ENGINEERING 13, 343 | 8 | 2008 |

*Question 1:*

*The topic of this PhD has been very fast developing research area and every month new important results are presented. Could you provide an overview of the most recent results in your topic?*

*Question 2:*

*Who have been the main authors who sited your work and their relation to your research? Would you present 5 main cases?*

## Answer to Question 1 and 2:

Environmental sustainability is posing unprecedented business challenges, and is a major topic of international debate. Social, economic and political concerns about rising GHG levels in the atmosphere, and escalating use of natural resources (e.g., oil) spurred by economic globalization, have prompted a wave of voluntary and mandatory initiatives for monitoring and reducing the environmental impacts associated with many industries.

The importance of developing decision support systems to evaluate the environmental impact of different options, not only related to the field of waste to energy and waste management, has been confirmed by the numerous research papers appeared recently in many journals.

One of the key elements is to derive an environmental impact measure that, while easily understandable by the main stakeholders, is also relatively easy to calculate.

Torres et al (2012) developed a procedure that provides a performance evaluation and comparison between different alternatives of the plant through the calculation and aggregation of environmental and economic indicators. The results obtained are organized on a cockpit chart based on the Environmental Strategy Map (De Benedetto, Klemes 2009) and give insights into the plant environmental behavior, being very useful to find the suitable modifications in operation and topology of the plant. Moreover, the use of this tool allows the implementation of optimization algorithms and heat integration strategies, with the aim of minimizing resources consumption, pollutants releases, energy requirements and total costs.

In the field of Waste to Energy, Herva and Roca (2012) analyzed the use of Ecological footprint (EF) and Multi-criteria analysis, in the evaluation of four different options of MSW treatment.  The ecological footprint (EF) proposes a single composite indicator, while multi-criteria analysis (MCA) integrates the EF together with other material flow indicators related to water consumption, emissions to air and water and occupied landfill volume. In environmental evaluation assessments usually an exhaustive data collection is required to obtain reliable results. However, this also means that huge amounts of information of different nature must be handled, which may complicate the analysis. In this respect, the EF is particularly appealing because it allows synthesizing the results in a single score, even though this aggregation means that it partially loses its capacity to formulate specific targets. Moreover, indicators expressed in territorial dimensions are easier to be interpreted by all the stakeholders, given that the documented ecological demand can be compared to the biosphere’s regenerative capacity. Hence, it could be helpful in determining the ability of an industrial system to adapt to the local natural limiting factors. It also has the advantage of being a composite indicator that does not rely on the assignment of weights based on expert opinion; rather, the aggregation is carried out using empirical coefficients related to the productivity of the different area types considered.

Bovea and Prez (2011) provide a thorough overview of different evaluation methods along the design life cycle of products. The paper reviews the most important support tools for decision making and maps them against the different product design phases. The Environmental Strategy Map illustrated in De Benedetto, Klemes (2009), ranks as one of the easiest tools to be used for Design alternative evaluation and best alternative selection. This study confirms the importance of the work presented in the PhD study as a valid answer to the question of decision support making in environmental sustainability.

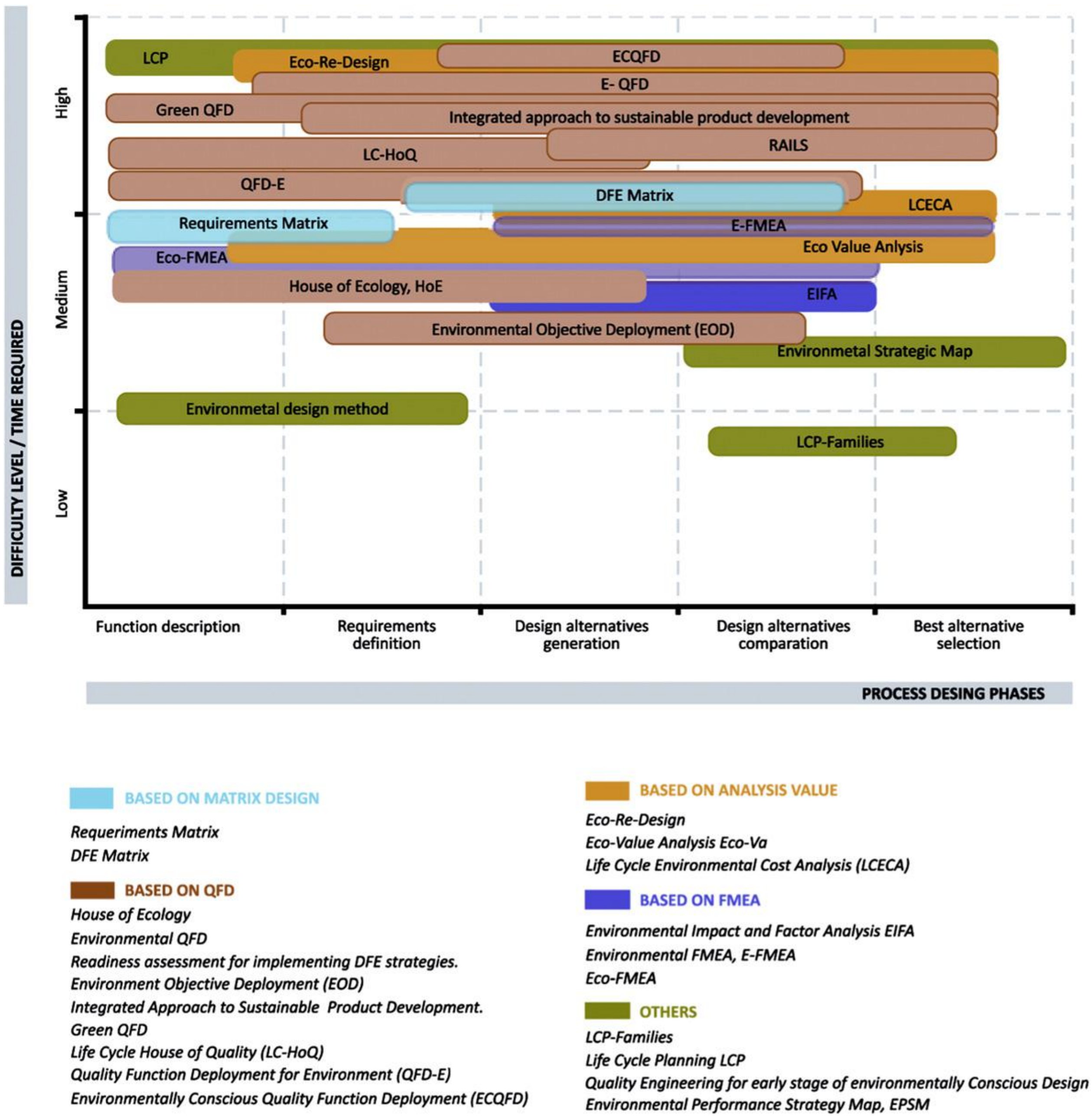


Fig 1. Adapted from Bovea and Perez (2012)

Moving towards sustainability requires the redesigning of production, consumption, and waste management. Reliable definitions and measurements are necessary for achieving these goals.
Cucek (2012) provides a review of existing methods, including the Environmental Strategy Map (De Benedetto, Klemes 2009) and calls for further extension of the concept to integrate environmental, social and financial considerations. One of the main findings of the paper is that while usage of environmental footprints is particularly widespread and therefore, such footprints are being defined more frequently and their units clearly expressed. In contrast, social and economic footprints are still rarely used. This study shows that Carbon Footprint, Energy footprint, and economic footprints are not yet standardized and are still an open issue. While the Environmental Strategy map offers an opportunity to combine different aspects in one evaluation tool, these perspectives on the footprints, and extended LCA indicate that substantial work remains in order to properly integrate economic, environmental, and social considerations during decision-making.

While LCA models are developed for assessing the environmental impacts, it is also important to extend the horizon and compare complex systems from an overall sustainability performance. However, in generic LCA-methodology, LCA results include several different environmental impact categories, which creates complexity if there is an emphasis on comparing industrial sectors.

Based on the work described in the first article derived from the study of this PhD Thesis (De Benedetto, Klemes 2009), and trying to answer the need for providing an overall environmental impact score that combines the selected impact categories for industrial sectors, Egilmez, Kucukvar and Tatari (2013) integrate Economic

Input-Output Life Cycle Assessment (EIO-LCA) and Data Envelopment Analysis (DEA), a linear programming-based mathematical optimization model, to analyze the eco-efficiency of manufacturing sectors. In this way they compare different sectors from and environmental sustainability point of view and they also proceed into a supply chain decomposition analysis – an approach similar to the Environmental Technology Routing described in De Benedetto, Klemes (2010).

The Environmental Bill of Material and Technology Routing (De Benedetto Klemes 2010) is also cited, and its idea developed into an evaluation of the different elements that contribute to the impacts of a logistic chain by Sellito et al (2011). The environmental performance of this logistic chain was divided in 5 constructs: atmospheric emissions, liquid effluents, solid waste, usage of energy and management and law accomplishments. These constructs were ranked in importance by experts in environmental management and were appraised by indicators. In this way the method offers a normalized performance index, ranking from 0 to 100% and it reflects the irreversible path of the environmental performance of the operations.

Involvement of stakeholders as well as easy ways to communicate environmental impacts are also paramount.

Hanan, Burnley and Cooke (2012) investigated the use of Multi-criteria Decision Analysis (MCDA) was investigated to assess the options for managing waste paper. Seven recycling, recovery and disposal options were considered by the panel who evaluated each option against seven environmental, financial and social criteria. The idea presented is to combine the technical aspects of the waste management technologies under review with results of a life cycle assessment, the financial costs of each option and relevant national legislation and waste recycling/recovery targets. The panel decides then the weighting and the importance to associate to each category. The balanced evaluation of the different options provides a decision ranking. While the method can be considered a simple and relatively powerful way to include different stakeholder in the decision process, lack of understanding of the LCA results, as well as bias due to the way these LCA results are presented can limit the use of this method.

Arena, Azzone and Conte (2012) developed a performance measurement system that helps carmakers assess their technological options for sustainable mobility. Based on an analysis of the relevant scientific
and practitioner literature, they put together a set of key sustainability indicators for the different stages of
the car lifecycle: raw material extraction, material production, product manufacture, product use, end of life, and transport. The resulting model was then validated by a panel of experts, and compared with lifecycle analysis (LCA). From a practitioner perspective, this model seeks to resolve the common trade-off between comprehensiveness of analysis and feasibility of data collection.

While performing LCA or while elaborating sustainability indicators based on LCA, the quality and the availability of data is sometimes a limiting factor. Accounting for uncertainty estimation can be also a challenge.

Wang and Sheng (2012) present a hybrid stochastic method to improve the uncertainty estimate in LCA with data limitations. This method can be a valuable tool especially to evaluate deterministic results of LCA of complex product system (e.g. building) when uncertain information is needed for decision-making.

Compared to deterministic results, probabilistic results were often considered more reliable when large data uncertainties existed, such as data uncertainties in embodied energy coefficients of building materials. Both the statistical and Data Quality Indicator methods have been used to estimate data uncertainties in LCA. However, neither of those alone is adequate to address the challenges in LCA of complex product system, due to the large quantity of material types and data scarcity. This paper presents a hybrid method, which combines Data Quality Indicator and the statistical method by using a prescreening process based on Monte Carlo rank-order correlation sensitivity analysis. By optimizing the utilization effect of the available statistical data, this hybrid method can increase the reliability of the uncertainty estimate compared to the pure data indicator method.

Question 3: Could you explain the main conclusions of Chapter 4?

Answer to Question 3:

Fuzzy logic has been successfully applied to the simplifying of decision making in environments characterized by uncertainty and imprecision. The main idea is to build a model that simulates the way an expert reason (from which the definition of Expert System). The difference of fuzzy inference to traditional mathematical models are that the relation between inputs and outputs are not determined by complex equations, but by a set of logical rules, reflecting an expert's knowledge (Gonzalez et al. 2002).

Nowadays it is obvious that LCA is an efficient tool for improving product design in compliance with environmental issues. Practitioners and researchers have largely discussed the way of spreading LCA to all kind of companies. One of the main limitations of applying LCA, even for large corporations, is the availability and quality of data. For small and medium-sized enterprises the major problems are lack of knowledge, resources, awareness or time. The work presented in Chapter 4, represents a way to deal with the uncertainty of the data and therefore a possibility to make a tool like the Environmental Strategy Map available to all kind of practitioners.

In particular, Chapter 4 proposes the definition of an inference system to define a detailed value (crisp value) for the footprints at the basis of the Environmental Strategy Map through the steps of:

1. definition of the fuzzy variables (input and output variables)
2. definition of the membership functions for all variables
3. definition of the fuzzy rule set.
4. assuming that membership functions of all impact categories is similar to triangular fuzzy numbers, a total positive or negative fuzzy value for the environmental impacts is going to be calculated.
5. finally the defuzzification will lead us to the punctual impact estimator and its corresponding uncertainty interval.

Since the use of fuzzy inference implies substituting crisp results by results belonging to fuzzy sets with certain degree of admitted variability, the main drawback of this method can be the loss of accuracy in comparison with traditional quantitative ones. However, results offered can be very helpful during the first iterations of LCA, to detect the main focus of environmental burdens along life cycle of the product and to focus further efforts on them (Gonzalez et al. 2002).

The work presented in Chapter 4, proposes a way of dealing with uncertainty in the input data. It also offers the opportunity of reducing the need of environmental knowledge when applying LCA by applying fuzzy logic. The definition of an inference model has the advantage of avoiding the use of specific weighting factors and the need to rely on judgements made by the practitioner.

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