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A methodological framework of eco-efficiency based on fuzzy logic and Life Cycle Assessment applied to a Mexican SME

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ABSTRACT

In this paper an eco-efficiency analysis methodology that takes into account Life Cycle Assessment (LCA) and fuzzy logic is presented. It consists of four stages: (1) perform LCA and basic cost analysis, (2) normalize the environmental and economic impact categories results, (3) integrate economic and environmental impact categories by means of a fuzzy treatment and (4) obtaining the fuzzy eco-efficiency index. The result is a preference hierarchy that indicates an order of scenarios according to their degree of eco-efficiency. The methodology proposed is applied to a Mexican SME: a plastic products manufacturer. Six different supplier locations of polypropylene were considered: United States of America (transporting by land and by water), China, Singapore, Europe, and United Arab Emirates. The robustness of the methodological framework was tested by means of a comparative analysis with a decision surface graph, an eco-efficiency index, and random runs to prove their variability. Results show that USA is the most preferable supplier location when polypropylene is transported by land. The comparative analysis with the random series results and the decision surface graph, allowed to corroborate the stability of the fuzzy preference orders and to identify clusters of scenarios with an equally eco-efficient performance. Thus, the robustness of the methodology proposed was validated.

1. Introduction

Eco-efficiency was first conceived at the beginning of the 1990s by Schaltegger and Sturm (1992) and strongly promoted by Schmidheiny and the Business Council for Sustainable Development (1992), later known as World Business Council for Sustainable Development (WBCSD). Various definitions can be found in the literature, given the term's wide range of applications (Huppes & Ishikawa, 2005). For example, Verfaillie and Bidwell (2000) state that eco-efficiency implies maximizing creation of value while having minimized the use of resources and emission of pollutants. The WBCSD (2006) interprets it as the "delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity". Kicherer et al. (2007) defines it as the ratio between economic and environmental impact per functional or unitary unit and ISO 14045 (ISO, 2012) defines as a quantitative management tool which enables the study of life-cycle environmental impacts of a product system along with its product system value for a stakeholder. In this article, we consider eco-efficiency as the fuzzy relationship between economic and environmental impacts per functional unit.

Eco-efficiency methodologies, including ISO 14045 (ISO, 2012), that use impact categories are affected by a wide range of factors that increase uncertainty, such as lack of information, unknown interdependencies and high complexity (French & Geldermann, 2005; Guinée, 2002 and Tseng, Tan, Ming, Lin, & Yong, 2013). A way to consider uncertainty and ambiguousness, while presenting reliable results to decision-makers, can be achieved by applying the fuzzy set theory developed by Zadeh (1965). Fuzzy set theory is one of the most widespread decision methodologies in engineering, science and business, mainly because it has proven its usefulness to improve decision making by taking uncertainty into account (Mardani et al., 2015).

There is a need to develop eco-efficiency methodologies that consider uncertainty, so that these can be implemented in the decision-making processes and be used to achieve sustainability goals. Although several methodologies that successfully link economic and environmental factors exist in the literature (Cerutti et al., 2013; Figge & Hahn,

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2013; Hahn et al., 2010; Kicherer et al., 2007; Levidow, Palle, Asa, Sara, & Dionysis, 2016), only a few deal with uncertainty by means of fuzzy logic (Tseng et al., 2013Vakili-Ardebili & Boussabaine, 2007). In order to move forward in the path of more sustainable use of resources while improving productivity, organizations need an eco-efficiency methodology with low uncertainty levels that takes into account Life Cycle Assessment (LCA) and fuzzy set theory.

Inspired by the successful operationalization of the eco-efficiency analysis proposed by Kicherer et al. (2007) and ISO 14045 (ISO, 2012), this paper presents a methodological proposal that considers LCA and fuzzy set theory in order to minimize uncertainty in eco-efficiency analysis.

Linking economic and environmental factors and simultaneously considering uncertainty is the next big step in eco-efficiency analysis, so it can be a strong support in decision-making. As Michelsen et al. (2006) stated, eco efficiency and LCA are getting more and more attention as the private sector is realizing that "it is not only the individual companies that are competitors, but also the supply chain as a unit", which boosts the interest in improving performance in every step of the supply chain.

According to the last idea, in this paper, a methodological proposal for the eco-efficiency analysis –based on LCA and economic aspects– considering the uncertainty by means of fuzzy logic, is proposed and applied to a Mexican manufacturing SME of the plastic sector in order to test its functionality and as a manner to foster eco-efficiency in the industry in Mexico, where sustainable production and consumption is a national policy that must be adopted by this sector (SEMARNAT, 2013).

2. Eco-efficiency, LCA and fuzzy logic

Eco-efficiency was first introduced by the WBCSD (1992) as a tool to evaluate an organization's performance, by taking into account two aspects: a) economic prosperity and b) efficient use of resources. Robust environmental evaluations in eco-efficiency analysis were performed by some authors (Kicherer et al., 2007; Michelsen et al. (2006); Saling et al., 2002) by considering the use of LCA. The relevance of the introduction of LCA into eco-efficiency analysis was noted by Michelsen et al. (2006), who stated that the private sector was becoming aware of the need of improving performance in every step of the supply chain.

LCA is an objective and systematic methodology for determining environmental aspects and potential impacts associated with a product or service. LCA considers four phases: the scope definition, the Life Cycle Inventory Assessment (LCI phase), the Life Cycle Impact Assessment (LCIA) phase and the interpretation phase. The scope definition consists of establishing the goal, the functional unit, the system boundaries and the life cycle stages; these parameters depend on the subject and intended use of the study. The LCI phase consists in considering the input and output data of the system under study. In the LCIA phase, impact categories are obtained using the LCI results; the calculation of the impact categories' magnitude requires the use of reference information. Finally, in the interpretation phase, the results are analyzed; it includes a conclusion, the explanation of the limitations and a series of recommendations (ISO, 2006).

LCA results can be interpreted as the potential impacts generated by a product or service throughout its life cycle. The environmental impacts evaluated may be selected by the LCA practitioner, based on its relevance, in order to be considered as an input for eco-efficiency ratios.

Several eco-efficiency applications exist in the literature (Berkel, 2007; Hahn et al., 2010; Kicherer et al., 2007; Levidow et al., 2016; Park et al., 2015; Saling et al., 2002). Kicherer et al. (2007) improved the methodology presented by Saling et al. (2002) by linking environmental and economic factors through normalization and valorization. The end product of the analysis is a portfolio presentation that allows visualization of the output data and supports management decisions.

Economic and environmental factors have been successfully combined via normalization. But, as Kicherer et al. (2007) mentions, data quality decreases when more background data is used in the LCA inventory. This affects the usefulness of the analysis, according to Schaltegger and Sturm (1990) and Schaltegger (1997), which means that the uncertainty generated in the normalization step certainly imposes a barrier for decision making.

A framework published by Vakili-Ardebili and Boussabaine (2007) uses fuzzy logic to analyze economic and environmental indicators in order to obtain building design eco-drivers. To acknowledge high ambiguousness and subjectivity in the design decisions, the authors developed a fuzzy technique that involves the use of statistical parameters such as standard deviation and weighted arithmetic mean. Six eco-indicators for building assets were presented in a spider net diagram –design strategies, environmental impacts, design environmental strategies, social aspects, site analysis and economical aspects – to be classified as Minimum, Medium and Maximum Eco-efficiency design, defining bands of requirements and strategies for each level of eco-efficiency.

Fuzzy logic is a framework developed in the branch of mathematical logic that assigns to an object a degree of membership to a category between 0 and 1. The concept is based on the idea that a category's boundary is not well-defined, or in other words, that something more or less corresponds to a category. For example, conventional crisp set theory defines anyone higher than 1.80 m as a tall person and anyone below that level as a short person; fuzzy set theory, on the other hand, assigns a degree of membership to a 1.80 m person of 0.9 to the set of tall person and 0.1 to the set of not tall person (Kaufmann and Gil Aluja, 1987). As confirmed by Arfi (2005), membership functions are defined in a continuous interval [0, 1], rather than the Boolean pair {0 (out), 1 (in)}.

Fuzzy set theory is widely used in the present, as it is recognized as a key tool for understanding and expressing the problems a decision maker faces, and provides a rigorous mathematical framework in which imprecise phenomena can be studied (Tsai, 2009; Zimmermann, 1991).

Fuzzy set theory has been applied to LCA by several authors (Afrinaldi & Zhang, 2014; Geldermann et al., 2000; González et al., 2002; Güereca et al., 2007; Weckenmann & Schwan, 2001). Geldermann et al. (2000) used this tool along with a multi-criteria decision-making algorithm to support decision-making from LCA results. Weckenmann and Schwan (2001) studied the variability and uncertainty of data in inventories. González et al. (2002) used it to simulate the reasoning of an environmental expert. It outstands Güereca et al. (2007), who proposed a methodology that allows decision analysis considering the uncertainty involved in the LCA results. Afrinaldi and Zhang (2014) applied fuzzy logic to LCA, proposing a novel normalization and aggregation method based on targets for emission reduction and fuzzy inference systems, respectively.

Uncertainty is the main reason behind our proposal. To measure it, there are several methods in the literature. Heijungs and Huijbregts (2004) group them as follows: conventional – based on statistics – and non-conventional. The former – such as the hypothesis proof – is based on the variance, and the latter refers to more complex methods, like fuzzy logic.

3. The methodological framework of eco-efficiency based on fuzzy logic

The methodological framework proposed in this paper considers a fuzzy approach for eco-efficiency analysis in four steps: (1) perform LCA and basic costs analysis, (2) normalize the environmental and economic impact categories results, (3) integrate economic and environmental impact categories by means of a fuzzy treatment and (4) obtaining the fuzzy eco-efficiency index.

3.1. Perform LCA and basic cost analysis

This step consists on performing the LCA of the product or services