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A fuzzy logic based aggregation method for life cycle impact assessment

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ABSTRACT

The objective of this paper is to propose an alternative methodology for normalization and aggregation in life cycle assessment (LCA). The proposed normalization approach is based on target on emission reduction and the aggregation approach is done through fuzzy inference system. A sensitivity analysis methodology is also presented in order to quantify the magnitude of change in index of total environmental improvement when quantity of a particular emission changes. Index of total environmental improvement of a product is computed by utilizing the proposed methodology in order to demonstrate its applicability. The results show that the methodology is simple and effective.

1. Introduction

Resource depletion, global warming, climate change and other environmental problems increase society's environmental awareness. As a result, businesses and industries are forced to measure and reduce their environmental impacts. One of the tools that can be used is life cycle assessment (LCA). According to ISO standards, LCA consists of four phases: (1) goal definition and scoping, (2) inventory analysis, (3) life cycle impact assessment (LCIA) and (4) interpretation (ISO 14044, 2006). Furthermore, LCIA is composed by (EPA, 2006): (1) impact categories selection and definition, (2) classification, (3) characterization, (4) normalization, (5) grouping, (6) weighting and (7) evaluating and reporting. ISO standards state that the first three steps are compulsory. Normalization, grouping and weighting are optional. However, normalization and weighting can add valuable information to the decision makers because normalization allows impact to be compared among impact categories and weighting reflects stakeholders' goals and values (Hertwich and Pease, 1998; EPA, 2006).

1.1. Normalization and weighting in LCA

Regarding the reference value of normalization in LCA, Guinée et al. (2002) states that,

> *"The reference information may relate to a given community (e.g. The Netherlands, Europe or the World), person (e.g. Danish citizen) or other system, over a given period of time. Other reference information may also be adopted, of course, such as future target situation."*

Therefore, it is possible to use targets as the reference value of LCA normalization process.

In weighting, the use of distance to target method receives criticisms. In this paper the criticism is explained by using the mathematical derivation found in Lee (1999). The normalized impact for impact category type i is given by,

$$\mathrm{NI}_i = \frac{\mathrm{CI}_i}{N_i} \tag{1}$$

where NI_i is the normalized impact on impact category i, CI_i is the characterized impact and N_i is the reference value. The weighted impact (WI_i) is the product of NI_i and a weighing factor W_i,

$$\mathrm{WI}_i = \mathrm{NI}_i \times W_i \tag{2}$$

According to the distance to target method (Lee, 1999),

$$W_i = \frac{N_i}{T_i} \tag{3}$$

T_i denotes the target.

Substituting (1) and (3) to (2) results,

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$$WI_i = \frac{CI_i}{N_i}\frac{N_i}{T_i} = \frac{CI_i}{T_i} \quad (4)$$

Guinée et al. (2002), Seppälä and Hämäläinen (2001), Finnveden (1999) and Lee (1999) argue that Equation (4) proves that the distance to target method is not a weighting method, but just another form of normalization. Moreover, they agree that it fails reflecting the relative significance among impact categories because it assumes that all targets are equally important. Finnveden (1999) states that,

> *"The available distance-to-target methods are all based on the assumption that all targets are equally important. This is a critical assumption, which apparently has never been justified."*

By considering this, Lee (1999), Eco-Indicator 99 (Goedkoop and Spriensma, 2000) and Impact 2002+ (Jolliet et al., 2003) use the following equation,

$$WI_i = \frac{CI_i}{N_i}f_i \quad (5)$$

where the value of f_i reflects the relative significance/seriousness of impact/damage category i, and in some methods N_i is expressed as impact/damage per year per capita.

It is clear that, in Equation (5), the normalized impact CI_i/N_i is not aimed to facilitate the weighting process, and that is why f_i is presented. To determine f_i, Lee (1999) uses Analytical Hierarchy Process (AHP), Eco-Indicator 99 uses panel approach, and Impact 2002+ applies the mixing triangle approach. However, the value of f_i provided by the above approach may not reflect stakeholders' values and goals of a particular LCA study. That is why Eco-Indicator 99 methodology report (Goedkoop and Spriensma, 2000) states that "*In any case we encourage users to critically analyze the default weighting factors presented in this project (Eco-Indicator 99) and to propose other factors*".

Furthermore, problems may also arise with the use of N_i. In Eco-indicator 99, Impact 2002+, and CML 2001 (Guinée et al., 2002), European data is used and some values of N_i contains uncertainty because of lack of data on emissions for individual substances, lack of data for most European countries, lack of data for ozone layer depletion, and lack of data on heavy metals and pesticides emission to soil and water (Goedkoop and Spriensma, 2000).

1.2. Fuzzy inference system in LCA

Fuzzy inference system was introduced for the first time in 1965 by Zadeh (1965). It is widely used to elicit expert knowledge and model the human thinking process. Numerous authors also proposed the application of fuzzy inference system in LCA. Liu et al. (2012) used fuzzy set theory to quantify the probabilities and the severity of the impacts in a method combining risk assessment, LCA and multi criteria decision analysis. Benetto et al. (2006) applied fuzzy set theory to assess the impact of noise to humans due to lack of data, uncertainties and vagueness in noise impact assessment. Similarly, fuzzy set theory was also applied by Weckenmann and Schwan (2001) to handle uncertainty in inventory data. Güereca et al. (2007) proposed a two stages method, partial indicator acquisition and fuzzification, for LCIA valuation step. Seppälä (2007) improved and compared the fuzzy approach presented in Güereca et al. (2007) to the "traditional" valuation technique of LCA. González et al. (2002) simplified LCA process by fuzzifying the magnitude of the emissions.

It can be seen that the applications of fuzzy set theory in LCA are to handle uncertainty, to simplify LCA process by fuzzifying the magnitude of emissions and to value the characterization results in order to show the significance of impact category. For the latter application, by continuing fuzzy inference process to fuzzy IF-THEN rules, rule implication, aggregation and defuzzification, a single index can be resulted.

1.3. Objective of this paper

This paper attempts to improve the weaknesses found in the distance to target method and of using N_i as the reference value in the LCA normalization and weighting processes by proposing an alternative methodology. For impact assessment, the end-point approach is used in the proposed methodology. The proposed methodology allows sub damage categories and damage categories to be normalized and aggregated in order to produce an index of total environmental improvement. It is called an index of total environmental improvement because the proposed normalization procedure is based on the targets on emission reduction.

In order to quantify the significance among sub damage categories and damage categories, the dimensionless numbers produced by the normalization processes are treated as the inputs for the "weighting" processes. This process is done through fuzzy membership functions and fuzzy IF-THEN rules. The outputs of the above process are then aggregated by using fuzzy aggregation and defuzzification techniques. The result of the defuzzification process is the basis to compute index of total environmental improvement. The parameter of fuzzy membership functions and the structure of fuzzy IF-THEN rules are determined by the values and goals of the stakeholders.

The structure of the fuzzy inference system presented in this paper is based on Andriantiatsaholiniaina et al. (2004). The fundamental difference is that in Andriantiatsaholiniaina et al. (2004) the inputs for the normalization process are the environmental interventions, such as greenhouse gas emissions, NO_2 concentration and SO_2 concentration (quite similar to Gonzales et al. (2002)). The issue with their approaches is that it ignores the characterization step of LCA. Therefore, the magnitude of impacts/damages will never be known. Moreover, it does not seem appropriate to directly fuzzify the environmental loads because the relation between the loads and their damage categories is clear. In the proposed approach, the characterization process is done first and followed by the normalization process. Damage factors (before being normalized and weighted) provided by the existing methodologies (Eco-Indicator 99) is used to calculate damage on each sub damage category.

2. Material and methods

The proposed methodology consists of five steps: (1) normalize the damage value of each sub damage category, (2) aggregate the sub damage categories to their damage category using the fuzzy inference system, (3) normalize the defuzzification outputs of the fuzzy inference system applied to aggregate sub damage categories to produce index of environmental improvement for damage category, (4) aggregate the index of environmental improvement for damage category using the fuzzy inference system, and (5) normalize the defuzzification outputs of the fuzzy inference system applied for the index of environmental improvement for damage category to produce the index of total environmental improvement. It is shown by Fig. 1.

2.1. Normalize the damage value of each sub damage category

This normalization process is done for each sub damage category and will make fuzzy inference system possible. Outputs of this