# JCLP-Fuzzy Logic

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Journal of Cleaner Production 67 (2014) 159–172

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# A fuzzy logic based aggregation method for life cycle impact assessment

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ARTICLE INFO

*Article history:*
Received 25 April 2013
Received in revised form
27 November 2013
Accepted 6 December 2013
Available online 15 December 2013

*Keywords:*
Aggregation
Fuzzy logic
LCA
Normalization

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 impact. 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,

$$\mathrm{NI}_i = \frac{\mathrm{CI}_i}{N_i} \quad (1)$$

where $\mathrm{NI}_i$ is the normalized impact on impact category $i$, $\mathrm{CI}_i$ is the characterized impact and $N_i$ is the reference value. The weighted impact ($\mathrm{WI}_i$) is the product of $\mathrm{NI}_i$ and a weighing factor $W_i$,

$$\mathrm{WI}_i = \mathrm{NI}_i \times W_i \quad (2)$$

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

$$W_i = \frac{N_i}{T_i} \quad (3)$$

$T_i$ denotes the target.

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

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http://dx.doi.org/10.1016/j.jclepro.2013.12.010

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

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. (2008) 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 process, the normalized sub damage categories, are in the interval [0, 1], where zero is the worst and one is the best. The proposed normalization technique is based on the targeted reduction of emissions. Before formulating the equations for normalization, let us define $i = 1, 2, \cdots, I$ be substances in the life cycle inventory (LCI) table, $j = 1, 2, \cdots J$ be sub damage categories and $k = 1, 2, \cdots, K$ be damage categories. Furthermore, let us define the following.

BY = base year.
EY = evaluated year.
TY = target year.
$\tilde{H}_j^k$ = value of damage on sub damage category $j$ which belongs damage category $k$ in base year.
$H_j^k$ = value of damage on sub damage category $j$ which belongs damage category $k$ in evaluated year.
$\tilde{\tilde{H}}_j^k$ = targeted value of damage on sub damage category $j$ which belongs damage category $k$ in evaluated year.
$\tilde{x}_{ij}^k$ = amount of substance type $i$ emitted in base year which belongs to sub damage category $j$ of damage category $k$.
$x_{ij}^k$ = amount of substance type $i$ emitted in evaluated year which belongs to sub damage category $j$ of damage category $k$.
$h_{ij}^k$ = damage factor of substance type $i$ which belongs to sub damage category $j$ of damage category $k$.
$\alpha_{ij}^k$ = emission reduction of substance $i$ to be achieved in target year which belongs to sub damage category $j$ of damage category $k$, $0 < \alpha_{ij}^k < 1$.
$NH_j^k$ = the normalized value of damage on sub damage category $j$ of damage category $k$.

The normalized value of damage on a particular sub damage category is modeled as the following. First, a target year, base year and how much reduction of emission (usually in percentage) desired in the target year relative to the emission in the base year are defined. The percentages of reduction may come from internal, national or regional target. By using damage factors provided by Eco-Indicator 99 total damage on a particular sub damage category in the reference year and evaluated year can be calculated by using Equations (6)–(8). Furthermore, the target on a particular sub damage category in the evaluated year can be evaluated by utilizing the percentage of reduction. If, in the evaluated year, total damage on a particular sub damage category is less than or equal to the target then the normalized value of damage on that particular sub damage category is set to be 1, if total damage on a particular sub damage category is greater than or equal to the total damage in the base year then the normalized value of damage on that particular sub damage category is set to be 0, otherwise, the normalized value of damage is in the interval (0, 1) meaning that the target cannot be achieved but total emission is lower than the emission in the base year. The normalized damage value is calculated by using Equation (9). If equation (9) is plotted then its shape is trapezoidal as shown by Fig. 2. The notation for Equation (9) and the formulas used to

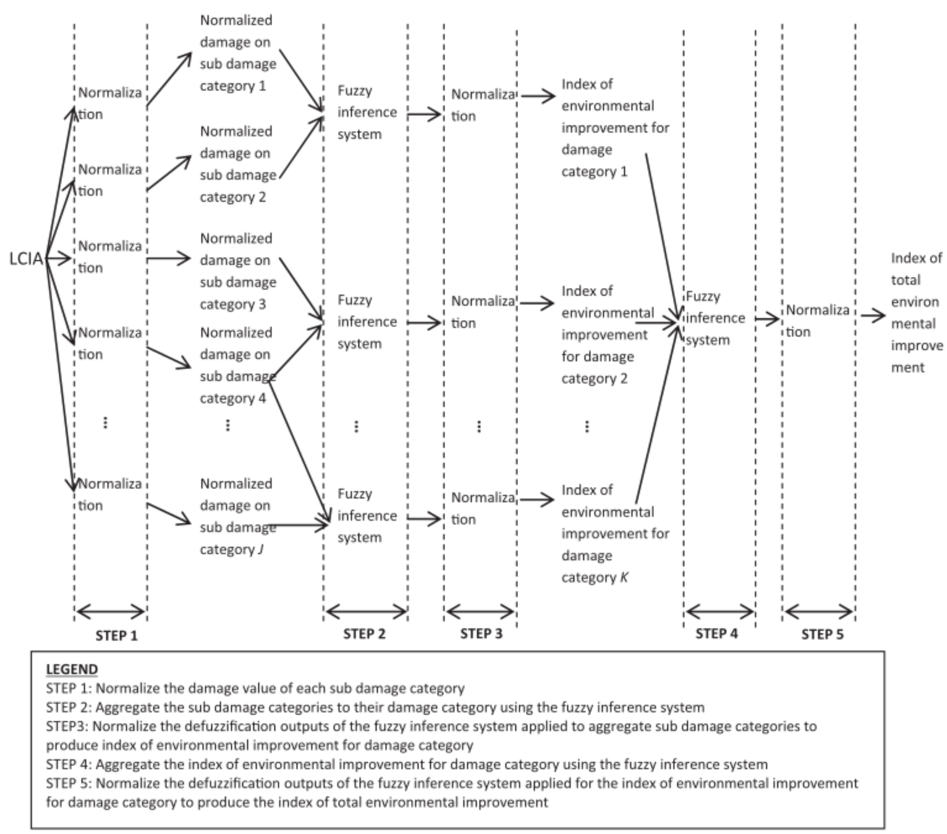



**Fig. 1.** Proposed method.

express membership functions, discussed in the next sections, follow the notations found in Mathworks (2013).

$$\bar{H}_j^k = \sum_{i=1}^{I} h_{ij}^k \bar{x}_{ij}^k \tag{6}$$

$$H_j^k = \sum_{i=1}^{I} h_{ij}^k x_{ij}^k \tag{7}$$

$$\tilde{H}_j^k = \sum_{i=1}^{I} h_{ij}^k \tilde{x}_{ij}^k \left[1 - \alpha_{ij}^k \frac{\mathrm{EY} - \mathrm{BY}}{\mathrm{TY} - \mathrm{BY}}\right] \tag{8}$$

$$\mathrm{NH}_j^k = max\left\{min\left\{1, \frac{\bar{H}_j^k - H_j^k}{\bar{H}_j^k - \tilde{H}_j^k}\right\}, 0\right\} \tag{9}$$

### 2.2. Aggregate the sub damage categories to their damage category using the fuzzy inference system

After sub damage categories are normalized, now fuzzy inference system for the normalized damage values can be conducted. In this methodology Mamdani's fuzzy inference process is applied because it is intuitive, mostly used and fits human thinking process (Sivanandam et al., 2007). The Mamdani's fuzzy inference process consists of five steps: (1) define and fuzzify input variables, (2) define and fuzzify output variables, (3) fuzzy IF-THEN rules, (4) rule implication, (5) aggregation and defuzzification (Sivanandam et al., 2007).

#### 2.2.1. Input variables

The normalized value of sub damage category $j$ which belongs to damage category $k$, $\mathrm{NH}_j^k$, is used as input variable. A membership function is then used to obtain the degree of membership of $\mathrm{NH}_j^k$ in a linguistic variable $v_p$, $p = 1, 2, \cdots, P$. As an example, the linguistic variables may be defined as $v_1 = bad$, $v_2 = good$ and $v_3 = very\ good$. The membership function of $\mathrm{NH}_j^k$ in linguistic variable $v_p$ is denoted as $\mu_{v_p}(\mathrm{NH}_j^k)$. The formulas for $\mu_{v_p}(NH_j^k)$ are given by Equations (10)–(12), where $a, b, c, d \in [0, 1]$ are the parameters of the membership functions. If Equations (10)–(12) are plotted then they will follow trapezoidal shape as shown by Fig. 3. The value of $\mu_{v_p}(\mathrm{NH}_j^k)$ represents the "*grade of truth*" of $\mathrm{NH}_j^k$ to be in linguistic variable $v_p$. Note that the membership function can only take value of real number in the interval [0,1] (Zadeh, 1965). Therefore $\mu_{v_p}(\mathrm{NH}_j^k) \in [0, 1]$ for every $v_p$, $j$, $k$ and for any forms of membership function.

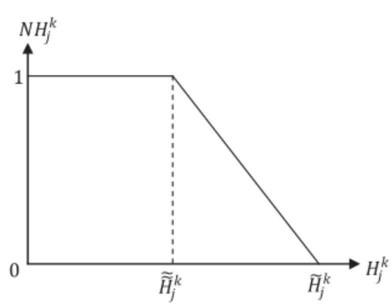


**Fig. 2.** The normalization function of sub damage category $j$ of damage category $k$.

$$\mu_{v_p}\left(\mathrm{NH}_j^k\right) = \max\left\{\min\left\{\frac{\mathrm{NH}_j^k - a}{b - a}, 1, \frac{d - \mathrm{NH}_j^k}{d - c}\right\}, 0\right\}, a \neq b \neq c \neq d \tag{10}$$

$$\mu_{v_p}\left(\mathrm{NH}_j^k\right) = \max\left\{\min\left\{\frac{\mathrm{NH}_j^k - a}{b - a}, 1\right\}, 0\right\}, a \neq b, c = d \tag{11}$$

$$\mu_{v_p}\left(\mathrm{NH}_j^k\right) = \max\left\{\min\left\{1, \frac{d - \mathrm{NH}_j^k}{d - c}\right\}, 0\right\}, a = b, c \neq d \tag{12}$$

#### 2.2.2. Output variables

The fuzzy set of damage categories, denoted as $H^k$, are defined to be output variables. In order to formulate the membership functions of $H^k$, consider $w_q$, $q = 1, 2, \cdots, Q$, be the linguistic variable for a damage category. As an example, the linguistic variables may be defined as $w_1 = very\ low$, $w_2 = low$, $w_3 = medium$, $w_4 = high$, $w_5 = very\ high$. The degree of membership of $H^k$ in linguistic variable $w_q$, denoted as $\mu_{w_q}(H^k)$, is quantified by using a membership function. If the membership function of $H^k$ follows the trapezoidal form then the formula for $\mu_{w_q}(H^k)$ is similar to the Equations (10)–(12). If it is triangular then $\mu_{w_q}(H^k)$ is given by Equation (13). Fig. 4 plots the triangular membership function of $\mu_{w_q}(H^k)$.

$$\mu_{w_q}\left(H^k\right) = \max\left\{\min\left\{\frac{H^k - a}{b - a}, \frac{c - H^k}{c - b}\right\}, 0\right\}, a \neq b \neq c \tag{13}$$

#### 2.2.3. Fuzzy IF-THEN rule

Fuzzy IF-THEN rules are used to link the linguistic variables of sub damage categories and the linguistic variables of damage categories. Rule is denoted as $r = 1, 2, \cdots, R$. The form of IF-THEN rule is shown by Table 1.

Below is an example of fuzzy IF-THEN rules.

Sub damage categories: Damage on resources caused by extraction of minerals and damage on resources caused by extraction of fossil fuels.
Damage category: resources
Rule 1: If (extraction of fossil fuels is "Bad") and (extraction of minerals is "Bad") then (Resources is "Very Low")
Rule 2: If (extraction of fossil fuels is "Bad") and (extraction of minerals is "Good") then (Resources is "Low")

#### 2.2.4. Rule implication

Rule implication is the process of combining fuzzy input variable and fuzzy output variable to a fuzzy set and it is done for each rule. In this methodology, the Mamdani's implication rule is used to map the degree of membership of sub damage categories to the degree of membership of damage categories.

Before implementing implication procedure, the degree of membership of damage categories resulted by each IF-THEN rule have to be determined. For this purpose a AND (MIN) operator is used. Let $\mu_{w_q}^{\mathrm{Rule}\ r}(H^k)$ be the degree of membership of damage category $k$ in linguistic variable $w_q$ resulted by rule $r$ and is calculated by using Equation (14). It is assumed that each rule has the same weight. After $\mu_{w_q}^{\mathrm{Rule}\ r}(H^k)$ is obtained then the Mamdani's implication rule is implemented by using Equation (15).

$$\mu_{w_q}^{\mathrm{Rule}\ r}\left(H^k\right) = \min\left\{\mu_{v_p}\left(\mathrm{NH}_1^k\right), \mu_{v_p}\left(\mathrm{NH}_2^k\right), \cdots, \mu_{v_p}\left(\mathrm{NH}_J^k\right)\right\} \tag{14}$$

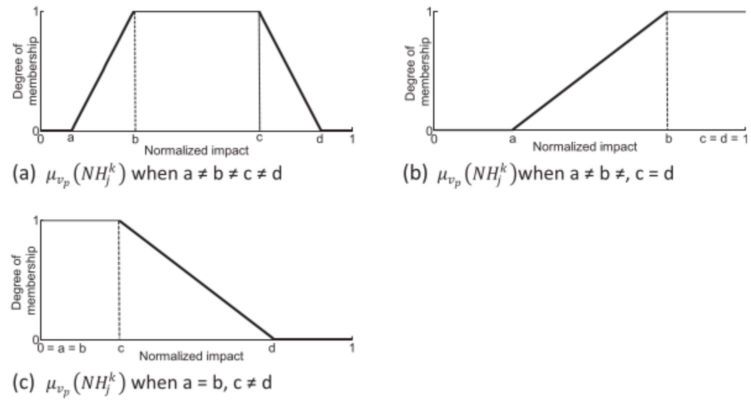



**Fig. 3.** Sub damage category membership function.

$$\phi_{\text{Rule } r}\left(H^k\right) = \min\left\{\mu_{W_q}^{\text{Rule } r}\left(H^k\right), \mu_{W_q}\left(H^k\right)\right\} \quad (15)$$

Below in an example of how rule implication is done.

Given that $\mu_{\text{bad}}(\text{NH}_{\text{Fossil fuels}}^{\text{Resources}}) = 0.5$ and $\mu_{\text{bad}}(\text{NH}_{\text{Minerals}}^{\text{Resources}}) = 0.2$. By using rule 1 and Equation (14), $\mu_{\text{Very low}}^{\text{Rule 1}}(H^{\text{Resources}}) = \min\{0.5, 0.2\} = 0.2$. Insert this result to Equation (15), $\phi_{\text{Rule 1}}(H^{\text{Resources}}) = \min\left\{0.2, \mu_{\text{Very low}}(H^{\text{Resources}})\right\}$. $\phi_{\text{Rule 1}}(H^{\text{Resources}})$ is a new fuzzy set shown by Fig. 5.

### 2.2.5. Aggregation

Aggregation is the process combining outputs of rule implication coming from each fuzzy rule to a fuzzy set. In aggregation process, fuzzy sets of damage categories produced by each applicable rule are aggregated to a new single fuzzy set. OR (MAX) operator is used in this methodology. The resultant of aggregation process for damage category $k$ is denoted as $\mu_{\text{Aggregated}}(H^k)$ and is given by Equation (16). Fig. 6 illustrates how aggregation is done.

$$\mu_{\text{Aggregated}}\left(H^k\right) = \max\left\{\phi_{\text{Rule 1}}\left(H^k\right), \cdots, \phi_{\text{Rule } R}\left(H^k\right)\right\} \quad (16)$$

### 2.2.6. Defuzzification

In order to get a single value of damage on each damage category then the aggregated fuzzy set is defuzzied. Defuzzification method used in this methodology is center of gravity and is given by Equation (17). Defuzzification processes is illustrated by Fig. 7.

$$\left(H^k\right)^* = \frac{\int_a^b \mu_{\text{Aggregated}}\left(H^k\right) H^k \mathrm{d}H^k}{\int_a^b \mu_{\text{Aggregated}}\left(H^k\right) \mathrm{d}H^k} \quad (17)$$

### 2.2.7. How membership function parameters and fuzzy IF-THEN rule are determined

In order to determine the parameters of the membership functions and the structure of fuzzy IF-THEN rules, the Delphi method is proposed to be used. Detail discussion on the Delphi method can be found in Dalkey (1969), Linstone and Turoff (1975), Riggs (1983), Ishikawa et al. (1993) and Hsu et al. (2010). In this paper, the experts are the stakeholders; their goals and values on sub damage and damage categories are elicited by using the Delphi method, and the numerical truth values of the linguistic variables are assigned by using the fuzzy inference system. The linguistic variables and the forms of the membership functions for the sub damage categories and damage categories can be predetermined or decided through another Delphi process.

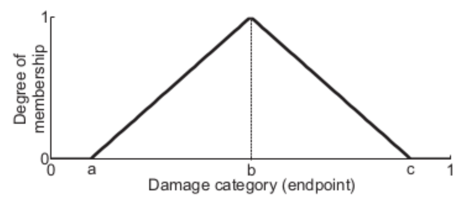



**Fig. 4.** Triangular membership function of $H^k$.

Given that the Delphi method is converged, the following illustrates how responses from the stakeholders are used to find the membership function parameters (Based on Hsu et al., 2010; Bovea and Wang, 2003). Assume that $\text{tra}_{ps} = \{a_{\text{ps}}, b_{\text{ps}}, c_{\text{ps}}, d_{\text{ps}}\}$ is the response from the $s^{\text{th}}$ stakeholder, $s = 1, 2, \cdots, S$, for the linguistic variable $v_p$ of $\text{NH}_j^k$. The parameters for the trapezoidal membership functions of $NH_j^k$ in linguistic variable $v_p$ are given by Equation (18)–(21) and illustrated by Fig. 8.

$$a_p = \min_s \{a_{\text{ps}}\} \quad (18)$$

$$b_p = \frac{1}{S}\sum_{s=1}^{S} b_{\text{ps}} \quad (19)$$

$$c_p = \frac{1}{S}\sum_{s=1}^{S} c_{\text{ps}} \quad (20)$$

**Table 1**
IF-THEN rule structure.

| Rule ($r$) | If $\text{NH}_1^k$ is | AND $\text{NH}_2^k$ is | ⋯ | AND $NH_j^k$ is | THEN $H^k$ is |
|---|---|---|---|---|---|
| 1 | $v_1$ | $v_1$ | ⋯ | $v_1$ | $w_1$ |
| 2 | $v_1$ | $v_1$ | ⋯ | $v_2$ | $w_1$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $R-1$ | $v_p$ | $v_p$ | ⋯ | $v_{p-1}$ | $w_Q$ |
| $R$ | $v_p$ | $v_p$ | ⋯ | $v_p$ | $w_Q$ |

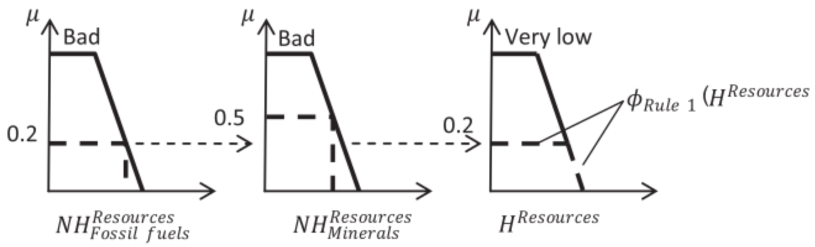



**Fig. 5.** Example of implication procedure.

$$d_p = \max_s \{d_{ps}\} \tag{21}$$

Similarly, consider that $tri_{qs} = \{a_{qs}, b_{qs}, c_{qs}\}$ is the response from the $s^{th}$ stakeholder for the linguistic variable $w_q$ of $H^k$. The parameters for the triangular membership functions of $H^k$ in linguistic variable $w_q$ are given by the following equations and illustrated in Fig. 9.

$$a_q = \min_s \{a_{qs}\} \tag{22}$$

$$b_q = \frac{1}{S}\sum_{s=1}^{S} b_{qs} \tag{23}$$

$$c_q = \max_s \{c_{qs}\} \tag{24}$$

### 2.3. Normalize the defuzzification outputs of the fuzzy inference system applied to aggregate sub damage categories to produce index of environmental improvement for damage category

The drawback of using center of gravity defuzzification technique is that the defuzzification outputs may never be equal to zero or one. This situation is illustrated by Fig. 10. As the consequence, $(H^k)^*$ may also never be equal to zero or one although all normalized values of sub damage categories are zero or one. It seems more logical to have $(H^k)^* = 0$ when all normalized inputs are zero and $(H^k)^* = 1$ when all inputs are equal to one. Therefore another normalization process is needed.

Before formulating the equation for the normalized value of damage on each damage category, consider the following notations.

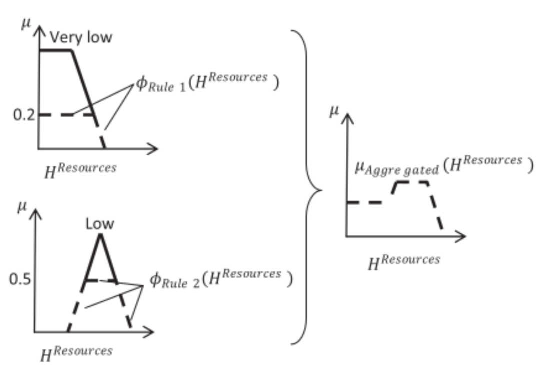



**Fig. 6.** Example of aggregation procedure.

$(H^k)^*_0$ = the defuzzification output of damage category $k$ when all normalized inputs are equal to 0.
$(H^k)^*_1$ = the defuzzification output of damage category $k$ when all normalized inputs are equal to 1.
$(H^k)^*_{\text{Normalized}}$ = the normalized defuzzification output of damage category $k$, $0 \le (H^k)^*_{\text{Normalized}} \le 1$. This is the index of environmental improvement for damage category $k$.

The idea is that we have to transform $(H^k)^*_{\text{Normalized}}$ to be zero if $(H^k)^* = (H^k)^*_0$, $(H^k)^*_{\text{Normalized}}$ to be one if $(H^k)^* = (H^k)^*_1$, otherwise $(H^k)^*_{\text{Normalized}} \in (0,1)$. For this purpose, simple interpolation technique is used and the result is given by (25).

$$(H^k)^*_{\text{Normalized}} = \frac{(H^k)^* - (H^k)^*_0}{(H^k)^*_1 - (H^k)^*_0} \tag{25}$$

### 2.4. Aggregate the index of environmental improvement for damage category using the fuzzy inference system

Fuzzy inference system for the normalized damage values follows the same procedure as fuzzy inference system applied for the normalized sub damage categories, but its input variable are the normalized damages on each damage category, $(H^k)^*_{\text{Normalized}}$. Membership functions and linguistic variables are defined for each normalized value of damage category. Through these membership functions, the degree of membership of each normalized damage category in each linguistic variable is obtained. This process produces several numbers. IF-THEN rules are applied along with fuzzy operator to obtain one number for each applicable rule. This single number is then mapped to the fuzzy sets of index of environmental improvement and reshapes its fuzzy sets. This is done for each rule and produces new fuzzy sets. The next process is to aggregate each fuzzy set produced by rule implication and the procedure is similar to the steps followed in fuzzy inference system for the normalized sub damage category. Finally, center of gravity method is applied to find the center point of the aggregated fuzzy set. This point is denoted as $E^*$.

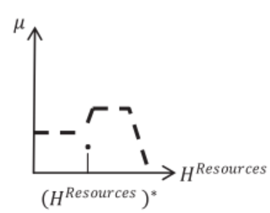



**Fig. 7.** Example of defuzzification procedure.

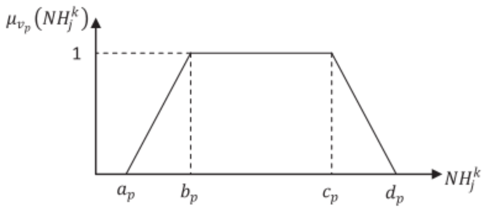



**Fig. 8.** The determination of trapezoidal membership function parameters.

### *2.5. 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*

This normalization process is the consequence of using center of gravity defuzzification technique in fuzzy inference system applied to the normalized damage value. $E^*$ may never be equal to zero although $(H^k)^* = 0, \forall k$, and may also never be equal to one although $(H^k)^* = 1, \forall k$. Therefore another normalization process is needed.

It is defined that $E_0^*$ be the defuzzification output of fuzzy inference system applied for the normalized damage value when $(H^k)^* = 0, \forall k$ and $E_1^*$ be the defuzzification output of fuzzy inference system applied for the normalized damage value when $(H^k)^* = 1, \forall k$. Then the index of total environmental improvement, EI, is given by equation (26).

$$\mathrm{EI} = \frac{E^* - E_0^*}{E_1^* - E_0^*} \tag{26}$$

However, normalizing the outputs of defuzzification processes has a drawback. It is seen when EI produced by normalization processes applied to the defuzzification outputs and EI produced without normalization processes applied to the defuzzification outputs are plotted, shown by Fig. 11.

Fig. 11 shows that the normalization processes give higher values of EI when $0.5 < \mathrm{NH}_j^k \le 1$, lower values of EI when $0 \le \mathrm{NH}_j^k < 0.5$. In other words, the use of normalization processes tend to give higher index of total environmental improvement if $\mathrm{NH}_j^k$ is greater than 0.5 and produce lower index of total environmental improvement if $\mathrm{NH}_j^k$ is less than 0.5.

### *2.6. Sensitivity analysis*

The purpose of the sensitivity analysis is to see how the change in the amount of a particular substance $(x_{ij}^k)$ will affect index of total environmental improvement (EI). It is known that an increase in $x_{ij}^k$ will decrease EI but the magnitude needs to be known. In order to find the magnitude of the effect, the first step is to check whether Equation (9) is continuous or not.

Equation (9) is not a smooth function, as shown by Fig. 2. It has sharp turning points exactly at $(\tilde{\tilde{H}}_j^k, 1)$ and $(\tilde{H}_j^k, 0)$. However, as

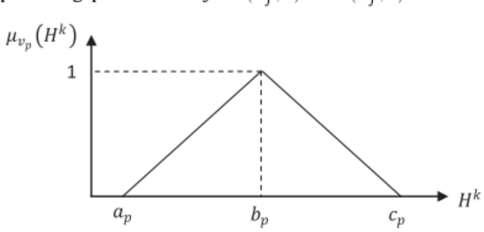



**Fig. 9.** The determination of triangular membership function parameters.

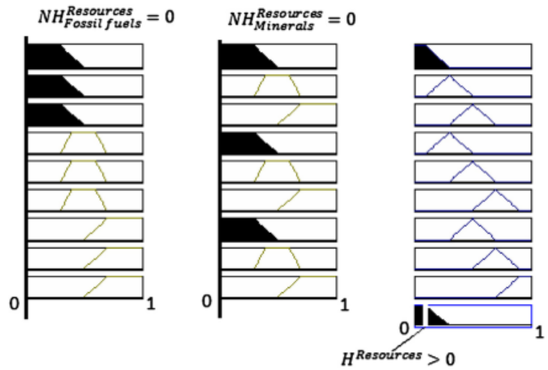



**Fig. 10.** Defuzzification values when all normalized inputs are zero.

$H_j^k \to \tilde{\tilde{H}}_j^k$, from both sides (left and right), $\mathrm{NH}_j^k(H_j^k) = 1$. Similarly, as $H_j^k \to \tilde{H}_j^k$, from both sides (left and right), $\mathrm{NH}_j^k(H_j^k) = 0$. Therefore $NH_j^k(H_j^k)$ is continuous everywhere. The second step is to check whether Equation (9) is differentiable or not. Limit of difference quotient is applied to check the differentiability of Equation (9) and given by Equation (27)–(30).

$$\lim_{H_j^k \to \tilde{\tilde{H}}_j^{k+}} \frac{\mathrm{NH}_j^k\left(H_j^k\right) - \mathrm{NH}_j^k\left(\tilde{\tilde{H}}_j^k\right)}{H_j^k - \tilde{\tilde{H}}_j^k} = \frac{-1}{\tilde{H}_j^k - \tilde{\tilde{H}}_j^k} \tag{27}$$

$$\lim_{H_j^k \to \tilde{\tilde{H}}_j^{k-}} \frac{\mathrm{NH}_j^k\left(H_j^k\right) - \mathrm{NH}_j^k\left(\tilde{\tilde{H}}_j^k\right)}{H_j^k - \tilde{\tilde{H}}_j^k} = 0 \tag{28}$$

$$\lim_{H_j^k \to \tilde{H}_j^{k+}} \frac{\mathrm{NH}_j^k\left(H_j^k\right) - \mathrm{NH}_j^k\left(\tilde{H}_j^k\right)}{H_j^k - \tilde{H}_j^k} = 0 \tag{29}$$

$$\lim_{H_j^k \to \tilde{H}_j^{k-}} \frac{\mathrm{NH}_j^k\left(H_j^k\right) - \mathrm{NH}_j^k\left(\tilde{H}_j^k\right)}{H_j^k - \tilde{H}_j^k} = \frac{-1}{\tilde{H}_j^k - \tilde{\tilde{H}}_j^k} \tag{30}$$

As the left and right limits are not equal then Equation (9) is not differentiable. However $-1/\left(\tilde{H}_j^k - \tilde{\tilde{H}}_j^k\right)$ can still be used to compute the change on $\mathrm{NH}_j^k(H_j^k)$ if $x_{ij}^k$ changes by $\Delta x_{ij}^k$. First, by applying the chain rule $\Delta\mathrm{NH}_j^k\left(x_{ij}^k\right)/\Delta x_{ij}^k = -h_{ij}^k/\left(\tilde{H}_j^k - \tilde{\tilde{H}}_j^k\right)$ is obtained and allows $\mathrm{NH}_j^k(x_{ij}^k + \Delta x_{ij}^k)$ to be determined. However, $\mathrm{NH}_j^k(x_{ij}^k + \Delta x_{ij}^k)$ have to be forced to be zero if it is less than zero and to be one if it is greater than one. For this purpose, MAX and MIN operators along with $\left(\tilde{H}_j^k - H_j^k\right)/\left(\tilde{H}_j^k - \tilde{\tilde{H}}_j^k\right)$ are utilized, shown by equation (31). By inputting $(\mathrm{NH}_j^k)_{\mathrm{new}}$ to the fuzzy inference process, the influence of $x_{ij}^k + \Delta x_{ij}^k$ toEI will be seen.

$$\left(\mathrm{NH}_j^k\right)_{\mathrm{new}} = \max\left\{\min\left\{1, \frac{\tilde{H}_j^k - H_j^k - \Delta x_{ij}^k h_{ij}^k}{\tilde{H}_j^k - \tilde{\tilde{H}}_j^k}\right\}, 0\right\} \tag{31}$$

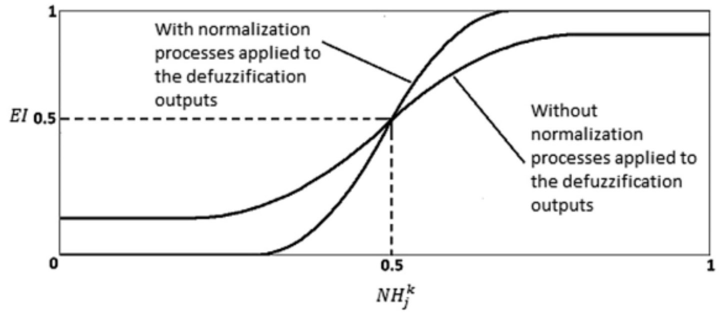



**Fig. 11.** Comparing the shape of index of total environmental improvement.

## 3. Results and discussion

In this section, the application and computational procedure of the proposed methodology are illustrated. Each step of the proposed methodology will be explained in detail. At the end of this section, the effect of change in amount of emissions to the index of total environmental improvement will also be explored.

In this case study LCIA of processes producing an engine is assessed. The life cycle stages considered are only material production, manufacturing and transportation (from material production facilities to manufacturing facilities). Use phase and end of life treatment are not included due to data limitation.

Method used for LCIA is Eco-Indicator 99 ((E, E) perspective) and the functional unit of this study is to manufacture one engine. Emissions data was obtained from emissions data in 2008 and 2012, where 2008 is considered as base year and 2012 as evaluated year. Sub damage categories and damage categories are defined in Table 2.

### 3.1. Normalize the damage value of each sub damage category

Values of damage on each sub damage category are calculated by using Equations (6)–(8). The damage factors are obtained from Eco-Indicator 99 ((E, E) perspective). As an example, damage to resources caused by extraction of fossil fuels is calculated, shown by Equation (32)–(34). The damage values are given by Table 3. It is assumed that the percentages of reduction by 2020 for crude oil and natural gas are 30% in material production, 25% in manufacturing and 20% in transportation. For coal, it is assumed that the percentages of reduction by 2020 are 25% in material production, 30% in manufacturing and 20% in transportation.

$$\bar{H}^{\text{Resources}}_{\text{Fossil fuels}} = 2694.310 + 2037.941 + 5.405 = 4737.66 \text{ MJ energy surplus.} \quad (32)$$

$$H^{\text{Resources}}_{\text{Fossilf fuels}} = 2519.669 + 2018.002 + 5.185 = 4542.86 \text{ MJ energy surplus.} \quad (33)$$

$$\tilde{H}^{\text{Resources}}_{\text{Fossil fuels}} = \begin{bmatrix} 179.520 \times \left(1 - 0.30 \times \frac{2012-2008}{2020-2008}\right) + \\ 19.788 \times \left(1 - 0.25 \times \frac{2012-2008}{2020-2008}\right) + \cdots \\ 0.046 \times \left(1 - 0.20 \times \frac{2012-2008}{2020-2008}\right) \end{bmatrix} = 4298.02 \text{ MJ energy surplus} \quad (34)$$

Substituting values resulted by Equations (32)–(34) to Equation (9) yields the normalized damage value for fossil fuels sub damage category, shown by Equation (35).

$$\text{NH}^{\text{Resources}}_{\text{Fossil fuels}} = \max\left\{\min\left\{1, \frac{4737.66 - 4542.86}{4737.66 - 4298.02}\right\}, 0\right\} = 0.443 \quad (35)$$

Values of damage ($H_j^k$) and target values of damage ($\tilde{H}_j^k$) for each sub damage category grouped according to product life cycle stage are presented in Fig. 12. Table 4 summarizes the normalized value of damage of each sub damage category. Fig. 12 shows that material transportation from material production facilities to manufacturing facilities has the least environmental damage. In contrary, material production and manufacturing processes have major contribution to the overall damage. Furthermore, Fig. 12 shows that no targets are achieved and it is confirmed by Table 4. In Table 4 all normalized values are in the interval (0, 1) which means that the processes produce less emission in 2012 but this improvement is still low and insufficient to achieve the targets. Having the results like this we can expect that the index of total environmental improvement is going to be low. Next step is to run fuzzy inference system using these normalized damages as the inputs. The following section illustrates the computational procedure and discusses the applicability of the proposed fuzzy inference system in order to produce the index of total environmental improvement.

**Table 2**
Sub damage categories and damage categories.

| Sub damage category | Damage category |
|---|---|
| Respiratory effects on humans caused by organic substance | Human health |
| Respiratory effects on humans caused by inorganic substance | |
| Human health effects caused by ozone layer depletion | |
| Human health effects caused by climate change | |
| Damage on resources caused by extraction of minerals | Resources |
| Damage on resources caused by extraction of fossil fuels | |
| Damage on ecosystem quality caused by the combined effect of acidification and eutrophication | Ecosystem quality |

**Table 3**
Damage values for resource damage category (MJ energy surplus).

| Resources | Life cycle stage | | | | | |
|---|---|---|---|---|---|---|
| | Material production | | Manufacturing | | Transportation | |
| | Damage in 2012 | Damage in 2008 | Damage in 2012 | Damage in 2008 | Damage in 2012 | Damage in 2008 |
| Crude oil | 174.198 | 179.520 | 18.659 | 19.788 | 2.956 | 2.951 |
| Coal | 2320.988 | 2488.800 | 1974.516 | 1991.040 | 2.185 | 2.407 |
| Natural gas | 24.483 | 25.990 | 24.827 | 27.113 | 0.043 | 0.046 |
| Total | 2519.669 | 2694.310 | 2018.002 | 2037.941 | 5.185 | 5.405 |

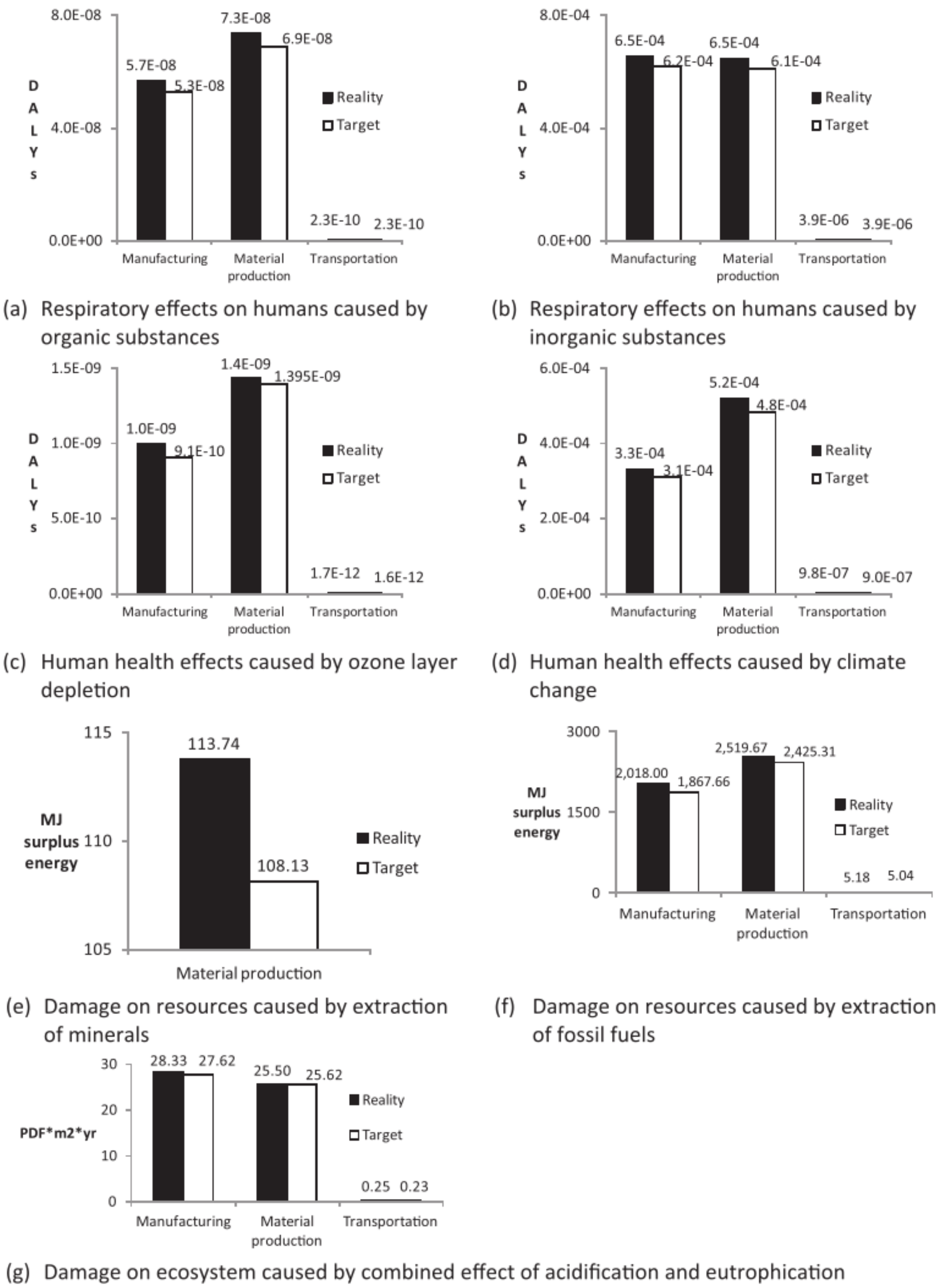



**Fig. 12.** Damage value on each sub damage category.

### 3.2. *Aggregate the sub damage categories to their damage category using the fuzzy inference system and normalize the defuzzification outputs*

In order to run fuzzy inference system, sub damage categories are defined as input variables and damage categories as output variables. The membership functions of sub damage categories and damage categories are shown by Fig. 13. The parameters of these membership functions are adopted from Andriantiatsaholiniaina et al. (2004). Fig. 13(a) shows that each sub damage category has three membership functions with "bad", "good" and "very good" linguistic variables.

Fig. 13(b) shows that the damage categories have five membership functions, two trapezoidal membership functions, their linguistic variables are "very low" and "very high", and three triangular membership functions, their linguistic variables are "low", "medium" and "high". For illustration, damage to resources is used as an example. From Table 4, it is known that $NH^{resources}_{Fossil\ fuels} = 0.443$ and $NH^{resources}_{Minerals} = 0.293$. Mapping these values to Fig. 13(a) or by inserting these values to Equations (10)–(12) yields $\mu_{Bad}(0.443) = 0.285$, $\mu_{good}(0.443) = 1$, $\mu_{very\ good}(0.443) = 0$, $\mu_{Bad}(0.293) = 1$ and $\mu_{Good}(0.293) = \mu_{Very\ good}(0.293) = 0$.

Note that, for resources, two sub damage categories (extraction of fossil fuels and minerals) have to be mapped to three linguistic variables ("bad", "good" and "very good"). Therefore, $3^2 = 9$ rules are used to map these sub damage categories to their damage category (resources). Applying these rules together with equation (14) produces the degree of membership of resources on each linguistic variable of the output ("very low", "low", "medium", "high" and "very high"). The IF-THEN rules are shown by Table 5.

The next step is to apply Mamdani's rule implication procedure. As shown by Table 5, only rule 1 and 4 that produce non-zero outputs. Therefore, implication outputs are determined by these two rules. By using Equation (15) the following results are obtained.

$$\phi_{Rule1}\left(H^{Resources}\right) = \min\left\{\mu^{Rule1}_{Very\ low}\left(H^{Resources}\right), \mu_{Very\ low}\left(H^{Resources}\right)\right\} = \min\left\{0.285, \mu_{Very\ low}\left(H^{Resources}\right)\right\}. \quad (36)$$

$$\phi_{Rule4}\left(H^{Resources}\right) = \min\left\{\mu^{Rule4}_{Good}\left(H^{Resources}\right), \mu_{Low}\left(H^{Resources}\right)\right\} = \min\left\{1, \mu_{Low}\left(H^{Resources}\right)\right\}. \quad (37)$$

The fuzzy sets of $\phi_{Rule1}(H^{Resources})$ and $\phi_{Rule4}(H^{Resources})$ are presented in Fig. 14. After completing rule implication steps, aggregation can be done by using equation (16). Equation (38) shows the resultant of damages on resources. Graphically the resultant is presented in Fig. 15.

$$\mu_{Aggregated}\left(H^{Resources}\right) = \max\left\{\phi_{Rule1}\left(H^{Resources}\right), \phi_{Rule4}\left(H^{Resources}\right)\right\} \quad (38)$$

The next process is to apply Equation (17) to obtain $(H^{Resources})^*$ and is given by the following.

$$\left(H^{Resources}\right)^* = \frac{\left(\int_0^{0.157} 0.285 H^{Resources} dH^{Resources} + \int_{0.157}^{0.3} \frac{H^{Resources} - 0.1}{0.3 - 0.1} H^{Resources} dH^{Resources} + \int_{0.3}^{0.5} \frac{0.5 - H^{Resources}}{0.5 - 0.3} H^{Resources} dH^{Resources}\right)}{\left(\int_0^{0.157} 0.285 dH^{Resources} + \int_{0.157}^{0.3} \frac{H^{Resources} - 0.1}{0.3 - 0.1} dH^{Resources} + \int_{0.3}^{0.5} \frac{0.5 - H^{Resources}}{0.5 - 0.3} dH^{Resources}\right)} = 0.263 \quad (39)$$

By inserting the value produced by equation (39) to equation (25), the normalized defuzzification output for damage to resources is obtained, as shown by the following.

$$\left(H^{Resources}\right)^*_{Normalized} = \frac{0.263 - 0.106}{0.894 - 0.106} = 0.199 \quad (40)$$

where $(H^{Resources})^*_0 = 0.106$, $(H^{Resources})^*_1 = 0.894$.

The same procedure is repeated for other damage categories.

### 3.3. Aggregate the index of environmental improvement for damage category using the fuzzy inference system and normalize the defuzzification outputs

Fuzzy inference system for the normalized damage value follows the same step as fuzzy inference system applied for the normalized damage value but the input variables are $(H^{Human\ health})^*_{Normalized}$, $(H^{Resources})^*_{Normalized}$ and $(H^{Ecosystem\ quality})^*_{Normalized}$. Defuzzification outputs of fuzzy inference system applied to the normalized damage value are then normalized by using Equation (26). The result is the index of total environmental improvement (EI). Table 6 summarizes index of environmental improvement for sub damage category, index of environmental improvement for each damage category and index of total environmental improvement.

### 3.4. Sensitivity analysis

Sensitivity analysis is done in two steps. Step 1, the change in $NH^k_j$ is calculated if emission of substance $x^k_{ij}$ changes by $\Delta x^k_{ij}$. This is done by using Equation (31). Step 2, the new value of $NH^k_j$ is inputted to the fuzzy inference system. A MATLAB SIMULINK

**Table 4**
Normalized sub damage category.

| Sub damage category | Normalized damage |
|---|---|
| Respiratory effects on humans caused by organic substance | 0.240 |
| Respiratory effects on humans caused by inorganic substance | 0.386 |
| Human health effects caused by ozone layer depletion | 0.355 |
| Human health effects caused by climate change | 0.183 |
| Damage on resources caused by extraction of minerals | 0.293 |
| Damage on resources caused by extraction of fossil fuels | 0.443 |
| Damage on ecosystem quality caused by the combined effect of acidification and eutrophication | 0.887 |

**Table 5**
IF-THEN rules for damage category resources and its rule implication outputs.

| Rule | IF $NH^{Resources}_{Fossil\ fuels}$ is | AND $NH^{Resources}_{Minerals}$ is | THEN $H^{Resources}$ is |
|---|---|---|---|
| 1 | Bad (0.285) | Bad (1) | Very Low (min{0.285,1} = 0.285) |
| 2 | Bad (0.285) | Good (0) | Low (min{0.285,0} = 0) |
| 3 | Bad (0.285) | Very Good (0) | Medium (min{0.285,0} = 0) |
| 4 | Good (1) | Bad (1) | Low (min{1,1} = 1) |
| 5 | Good (1) | Good (0) | Medium (min{1,0} = 0) |
| 6 | Good (1) | Very Good (0) | High (min{1,0} = 0) |
| 7 | Very Good (0) | Bad (1) | Medium (min{0,1} = 0) |
| 8 | Very Good (0) | Good (0) | High (min{0,0} = 0) |
| 9 | Very Good (0) | Very Good (0) | Very High (min{0,0} = 0) |

simulation model was developed to conduct the sensitivity analysis.

Here, the sensitivity analysis is illustrated by assuming an increase in total consumption of coal by 50 kg while other emissions/consumptions are kept unchanged. The result is the following.

$$\Delta x^{Resources}_{Coal;\ Fossil\ fuels} = 50\ \text{kg} \tag{41}$$

curve. As an example, according to Fig. 16(f), the decrease in fossil fuels consumption will have a significant effect on index of total environmental improvement. The maximum value of improvement that can be obtained from decreasing fossil fuels consumption is 0.25. This improvement will be achieved when the domain of the normalized value of damage is around 0.35–0.7. Otherwise, no improvement is made. When all the normalized damage are changed simultaneously then the index of total environmental improvement is given by Fig. 17 confirming Fig. 11.

$$\left(NH^{Resources}_{Fossil\ fuels}\right)_{new} = \max\left\{\min\left\{1, \frac{4737.66 - 4542.86 - 50 \times 2.04}{4737.66 - 4298.02}\right\}, 0\right\} = 0.211 \tag{42}$$

Inputting this new value to the fuzzy inference system yields new EI = 0.2464. Fig. 16 shows how the index of total environmental improvement change if each normalized sub damage category is varied according to a linear function. Note that, when a particular normalized sub damage category is varied the others are kept unchanged. Fig. 16 also illustrates how improvement should be made. The horizontal line of the curves in Fig. 16 infers that although a reduction in emissions results, it still will not change the index of total environmental improvement. In other words, the actual values of damage are decreased, but these improvements are insufficient to increase the index of total environmental improvement. Improvement on index of total environmental improvement will be gained when emissions are decreased along the curves that have a positive slope. Other valuable information that can be obtained includes the maximum and minimum values of index of total environmental improvement that can be achieved from varying a particular sub damage category. This information is given by the range of the

## 4. Conclusions

The main contribution of this research to cleaner production is that it provides a solution for the drawbacks found in distance to target and panel approach, which have been used in LCA normalization and weighting processes. As it is known, the distance to target method fails in reflecting the relative significance among damage categories. The panel approach has uncertainties in its reference value because of lack of data. Furthermore, the weighting factors used in the panel approach, found in Eco-Indicator 99 and Impact 2002+, may not fit values and goals of the stakeholders of a particular LCA study. In order to overcome this problem the proposed method uses target on emission reduction to normalize the damage values. The normalized damage values are then utilized as the input for the weighting process. This is done by eliciting values and goals of the stakeholders on each damage category by using fuzzy interference system. Fuzzy set operations are then applied to aggregate the damage values and produce the index of total environmental improvement. The proposed methodology simplifies the LCA

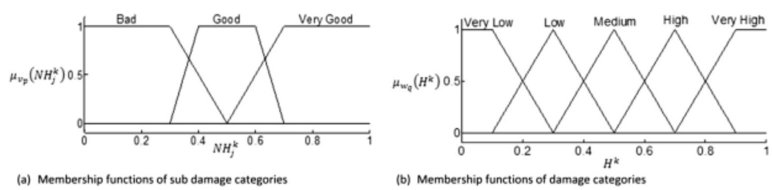



**Fig. 13.** Membership functions.

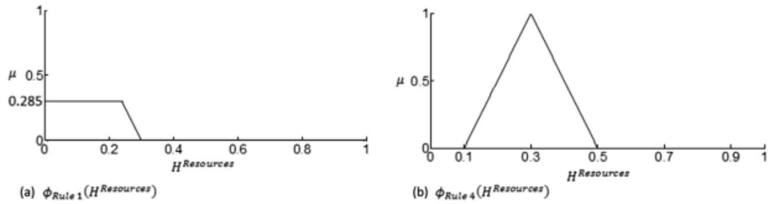



**Fig. 14.** Mamdani's rule implication outputs for damage to recourses.

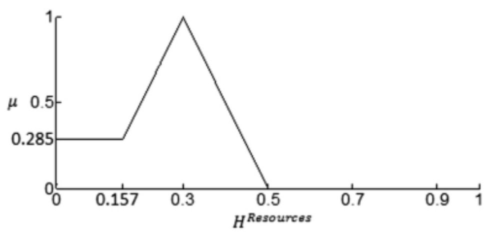



**Fig. 15.** Aggregation result, $\mu_{Aggregated}(H^{Resources})$.

normalization and weighting process and is expected to aid practitioners in evaluating environmental performance of their products.

The critical part of the proposed methodology is the determination of membership function parameters and the structure of IF-THEN rules. Triangular and trapezoidal functions are utilized in this method. In the case study, their parameters are taken from literature. In practice, membership function parameters and the form of IF-THEN rules have to be determined based on expert knowledge or values and goals of the stakeholders. A guideline to model expert knowledge and values and goals of the stakeholders as fuzzy membership function is provided. Furthermore, IF-THEN rules can also be weighted based on the expert knowledge or the values and goals of the stakeholders.

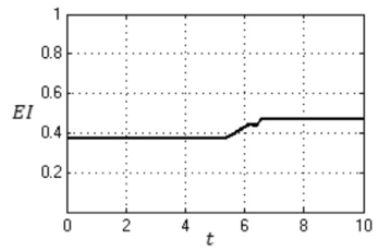
Since the proposed method focuses on the environmental improvement achieved by the product then it has several implications. Firstly, the proposed normalization technique is applicable when the goal of the stakeholders of the LCA study is to see how the environmental performance of a product improves according to a particular target. Secondly, the same value of index of total environmental improvement may have different absolute value of damage reduction. As an example, consider $\tilde{H}_j^k = 100, \tilde{\tilde{H}}_j^k = 87.5$ and $H_j^k = 90$ for product A. $\tilde{H}_j^k = 1000, \tilde{\tilde{H}}_j^k = 875$ and $H_j^k = 900$ for product B. BY = 2010, TY = 2020, EY = 2015 and $\alpha_{ij}^k = 0.25$ for both products. Applying Equation (9) results $NH_j^k = 0.8$ for both products. Note that the absolute reduction of damage caused by product A is 100–90 = 10 and the absolute reduction of damage of product B is 1000–900 = 100, but they have the same normalized value of damage, 0.8. This happens because the normalized value of damage is a relative index. Thirdly, it is strongly suggested to present both, the damage values and the indexes of total environmental improvement. This suggestion is made in order to avoid undermining the objectivity and benchmarkability of the LCA results. This is also supported by the results of the sensitivity analysis. As it is shown by the sensitivity analysis, even though a particular emission decreases, the index of total environmental improvement may not change. This is caused by MIN and MAX operator used in fuzzy inference system.

It is also important to note that the way the proposed index is interpreted is different from the way the existing indexes are interpreted. In the existing approaches, such as "point" used in Eco-Indicator 99, higher index means more damage (the lower the better). In the proposed method, a higher improvement index means environmental performance is increasing (the higher the better).

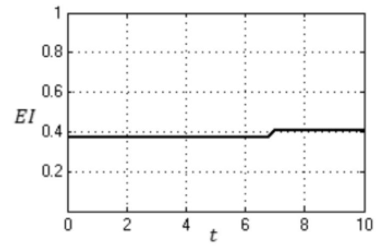
Furthermore, since the Delphi Method is used to define fuzzy membership function parameters and the fuzzy IF-THEN rules then the proposed methodology is only suitable for specific cases because there is no guarantee that the results of the Delphi Method can be applied for generic application (Finnveden, 1999). Therefore, the developed methodology is only applicable for internal product improvement applications.

**Table 6**
Index of environmental improvement for sub damage category, index of environmental improvement for each damage category and index of total environmental improvement.

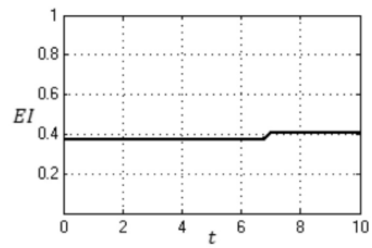
| Index of environmental improvement for sub damage category ($NH_j^k$) | Index of environmental improvement for damage category ($(H^k)^*_{Normalized}$) | Index of total environmental improvement (EI) |
|---|---|---|
| Respiratory effects on humans caused by organic substance = 0.240 | Human health = 0.127 | Index of total environmental improvement = 0.3715 |
| Respiratory effects on humans caused by inorganic substance = 0.386 | | |
| Human health effects caused by ozone layer depletion = 0.355 | | |
| Human health effects caused by climate change = 0.183 | | |
| Damage on resources caused by extraction of minerals = 0.293 | Resources = 0.199 | |
| Damage on resources caused by extraction of fossil fuels = 0.443 | | |
| Damage on ecosystem quality caused by the combined effect of acidification and eutrophication = 0.887 | Ecosystem quality = 0.887 | |



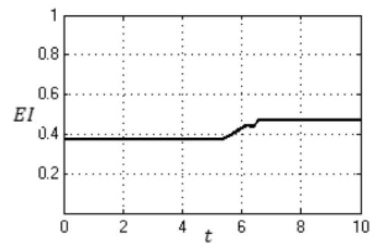

(a) Change in index of total environmental improvement when respiratory effects on humans caused by organic substance is varied according to $NH^{Human\ health}_{Respiratory\_organic} = 0.1t,\ t\epsilon[0,10]$



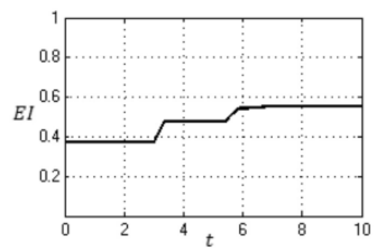

(b) Change in index of total environmental improvement when respiratory effects on humans caused by inorganic substance is varied according to $NH^{Human\ health}_{Respiratory\_inorganic} = 0.1t,\ t\epsilon[0,10]$



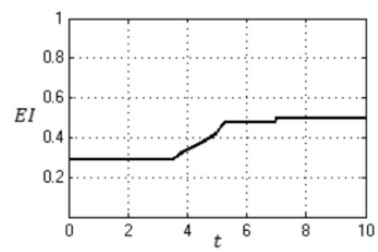

(c) Change in index of total environmental improvement when human health effects caused by ozone layer depletion is varied according to $NH^{Human\ health}_{Ozone} = 0.1t,\ t\epsilon[0,10]$



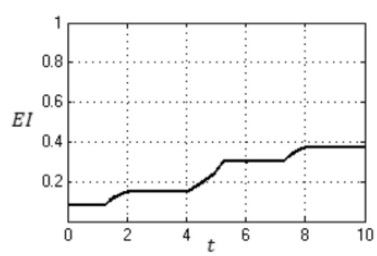

(d) Change in index of total environmental improvement when human health effects caused by climate change is varied according to $NH^{Human\ health}_{Climate\ change} = 0.1t,\ t\epsilon[0,10]$




(e) Change in index of total environmental improvement when mineral extraction is varied according to $NH^{Resources}_{Minerals} = 0.1t,\ t\epsilon[0,10]$




(f) Change in index of total environmental improvement when fossil fuels extraction is varied according to $NH^{Resources}_{Fossil\ fuels} = 0.1t,\ t\epsilon[0,10]$




(g) Change in index of total environmental improvement when combined effect of acidification and eutrophicationis varied according to $NH^{Ecosystem}_{Acidification\ and\ eutrophication} = 0.1t,\ t\epsilon[0,10]$

**Fig. 16.** Change in index of total environmental improvement when the normalized value of damage on each sub damage category is varied.

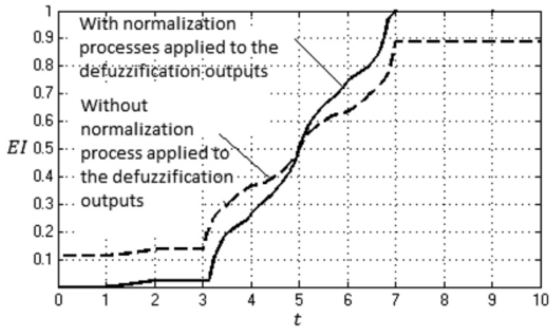



**Fig. 17.** The behavior of index of total environmental improvement when the normalized values of damage on each sub damage category are varied simultaneously.

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