LCA Methodology

Fuzzy Approach to Life Cycle Impact Assessment

An Application for Biowaste Management Systems

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Abstract

Background, Aims and Scope. In LCA the valuation step is very controversial since it involves value judgments. In order to strengthen the valuation step, this work establishes a new method, which includes normalization and weighting. Inspired by the proposal of Seppälä and Hämäläinen (2001), and based on the fuzzy sets theory (Zadeh 1965), this methodology permits information to be processed under uncertainty and subjectivity. The method proposed is applied to valuate five biowaste management system scenarios in the Metropolitan Area of Barcelona.

Methods. The valuation methodology proposed consists of the acquisition of partial environmental impact indicators, calculated on the basis of a characterized impact indicator (results from an LCA), an emissions inventory of the studied region, as well as the political targets and sustainability thresholds for a given area. Next, the partial indicator obtained is transformed to obtain a fuzzy linguistic descriptor, which permits the construction of a preference order amongst a series of alternatives.

Results. The proposed methodology permits the LCA normalization and weighting to be considered using a mathematically strengthened approach. It considers a semantic scale with eleven terms, which permits the gradual definition of the performance of alternatives according to their level of membership.

Discussion. This consideration deals with the uncertainty and subjectivity inherent in the data used. The results reveal that the worst biowaste management option is the scenario where all biowaste is collected selectively and treated only with biological processes. The preferred biowaste management scenario is the one in which direct uses of biowaste are considered.

Conclusions. The fuzzy approach considered improves the theoretical strength of the value obtained by the Distance to Target (DtT) method and its modification in accordance with Multi-Attribute Value Theories (MAVT). This permits the evaluation of complex systems, which are frequently placed in the field of subjectivity and uncertainty. This is therefore a good method of supporting the decision-making process, based on life cycle impact assessment results. In addition, the order of preferences obtained is consistent with the characteristics of each of the scenarios analyzed.

Recommendations and Perspectives. As future work, it is recommended that this methodology be applied to other situations, both in order to analyze its functionality and to compare the process defined with other fuzzy approaches, which may be appropriate for the valuation step in LCA.

Keywords: Biowaste management; decision-making; fuzzy sets theory; LCIA; multi-attribute value theory; valuation; weighting

Introduction

In Life Cycle Assessment (LCA) the step of valuation facilitates the interpretation of results and the decision-making process. Distance to Target (DtT) is one of the most commonly used methods to valuate alternatives in LCA. It entails obtaining measurements from the distance that separates the actual interventions (emissions) from the targets. Seppälä and Hämäläinen (2001) propose an adaptation of the DtT from the perspective of Multi-Attribute Value Theories (MAVT), which despite their theoretical foundation, present limitations in their practical applications, related to the uncertainty of the data.

On the other hand, DtT has been considered as a form of external normalization (Finnveden 1997, Lee 1999, Finnveden et al. 2002), in this case, some authors (Finnveden et al. 2002) suggest an additional weighting step in order to calculate the total environmental impact, but this process involves subjectivity due to the ideological elements.

In this work, a new method is established for the valuation step in LCA, inspired by the proposal of Seppälä and Hämäläinen (2001) and based on fuzzy sets theory (Zadeh 1965). This methodology permits the treatment of uncertainty and subjectivity, which are present in the process of obtaining an index by means of DtT methodology when using estimated data and weighting factors.

Fuzzy logic has been successfully applied to decision-making in environments characterized by uncertainty and imprecision.

In LCA, several recent studies have tried to apply fuzzy logic to deal with uncertainty. Geldermann et al. (2000) used fuzzy logic combined with multi-criteria decision-making algorithms to support decision-making from LCA results. Weckermann and Schwan (2001) applied the concept of fuzzy sets to deal with the variability and uncertainty of data contained in commercial databases. González et al. (2002) applied fuzzy inference at the assessment step of LCA, to simulate the reasoning of an environmental expert, allowing the company to obtain conclusions with lower requirements of certainty in the inventory data.

The methodology of valuation proposed is applied to valuate five scenarios of biowaste management systems for the Metropolitan Area of Barcelona.

1 Description of the Five Scenarios of Biowaste Management Systems

The LCA exposed in Güereca et al. (2005) has been taken as the basis for this work. **Table 1** presents the characteristics of the scenarios analyzed. The names of the scenarios respond, first, to the percentage of biowaste collected selectively; and, second, to the percentage of biowaste collected non-selectively. The term 'du' refers to the direct use of wastes (e.g. fish flour) and is used to differentiate the two alternatives 50–50. This table describes the percentage of biowaste managed by each treatment, the inputs of raw materials, electricity, and the functional unit for each scenario analysed.

The biowaste treatments used are composting, biogasification and incineration; also the direct use of biowaste is considered in one alternative. A landfill with baling-wrapping technology is included for the disposal of stabilized materials that are refused by the treatments; this process consists of the compression and wrapping of the waste with a stretch plastic film (Baldasano et al. 2003).

Table 2 shows the environmental profile with the potential environmental impacts generated by each scenario studied. Here, the scenarios are defined as alternatives $\{a_1, a_2, a_3, a_4, a_5\}$ and the impact categories as criteria $\{I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9, I_{10}\}$, according to the decision analysis context.

In order to generate the Life Cycle Inventory (LCI) Güereca et al. (2005) used the emission factors for the generation of electrical power reported by BUWAL 250 (1998); the emissions of composting reported by Flotats (2001); for biogasification, the data published in McDougall et al. (2001). For incineration, they estimated the emissions according to the Research Triangle Institute (RTI 1997), and in the case of controlled landfill, they used the data reported by Waste Management International (WMI 1994). The inventory was entered into the software 'Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, TRACI' of the U.S. EPA (Bare et al. 2003) and the results of this process are presented in Table 2.

In Table 2, the negative numbers respond to the approach of expanded boundaries (Finnveden 1999), adopted in Güereca et al. (2005). This approach considers as emissions saved the emissions that would be generated when producing the same quantity of electricity by the system analyzed, under the profile of Catalonia.

2 Methodology

This section describes the methodology of valuation proposed, which consist of two steps; the acquisition of a partial indicator, and the fuzzy treatment of this partial indicator.

Table 1: Characteristics of the scenarios analysed. (Source: Güereca et al. 2005)

Description/Scenario	78–22	50–50 du*	50–50	67–33	100–0
Selective collection (%)	78	50	50	67	100
No selective collection (%)	22	50	50	33	0
Compost manufacture (%)	30	15	25	34	50
Biogasification (%)	48	24	25	34	50
Incineration (%)	22	50	50	33	0
* Direct use (du) (%)	0	11	0	0	0
Landfilling by baling-wrapping technology (%)	7	3	5	6	9
Diesel (lts)	5.5E+06	5.4E+06	5.4E+06	5.4E+06	5.4E+06
Natural gas (m3)	2.1E+06	2.1E+06	2.1E+06	2.1E+06	2.1E+06
Electricity (input + or exported –) (kWh)	–1.1E+08	–1.6E+08	–1.6E+08	–1.2E+08	–1.1E+07
Water (m^3)	8.0E+05	4.2E+05	4.3E+05	5.7E+05	8.2E+05
Land use (has)	46	46	46	46	46
Total biowastes (Functional unit) (ton)	5.8E+05	5.8E+05	5.8E+05	5.8E+05	5.8E+05

Table 2: Characterized impact assessment by scenarios (Source: Güereca et al. 2005)

Environmental impacts / Scenarios	AC	EC	EU	FFU	GW	HHC	HH	HHNC	PS	WU
Weigths	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
78–22	0.000	0.000	0.000	0.770	0.000	0.000	0.000	0.000	0.000	0.400
50–50 du	0.000	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50–50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
67–33	0.000	0.000	0.000	0.000	0.050	0.000	0.000	0.000	0.000	0.000
100–0	0.000	0.000	0.910	0.000	0.000	0.000	0.000	0.000	0.000	0.000

AC=Acidification; EC=Ecotocixity; EU=Eutrophication; FFU=Fossil Fuel Use; GW=Global warming; HHC=Human Health Cancer; HH=Human Health Critery; HHNC=Human Health Non Cancer; PS=Photochemical Smog; WU=Water Use

2.1 The acquisition of a partial indicator

The equation of Ecoindicator 95 (Goedkoop 1995) adapted to the multi-attribute value theories (MAVT) by Seppälä and Hämäläinen (2001) is considered as the starting point of this paper (**Eq. 1**).

$$I(a) = \sum_{i=1}^{n} \frac{Ni}{Ti} \cdot \frac{Ii(a)}{Ni - Ii^{TH}} \quad (1)$$

where:

$I(a)$ = total environmental impact result caused by alternative *a*
Ni = normalization reference for impact category *i*
Ti = target reference of impact category *i*
$Ii(a)$ = indicator result of impact category *i* caused by alternative *a*
Ii^{TH} = threshold reference indicator for impact category i

The normalization reference (Ni), is the total characterized impact indicator result calculated based on an inventory of the whole society's activities in a given area and over a reference period of time (Consoli et al. 1993, Wentzel et al. 1997) and the Target reference (Ti) is based on political issues. In the case of fossil fuel use and water use, estimations are used instead of targets because targets do not exist. The threshold reference indicator (Ii^{TH}) is the point below which there is no remaining damage. In this case, we estimate the sustainable emissions. **Table 3** shows the reference area for each impact category, the period considered, the data sources and the values of Ni, Ti and Ii^{TH}.

Owing to the fact that the potential impact has a different order of magnitude in each environmental category, the changes that are produced in these potential impacts affect the global impact indicator (I(a)) proposed by Seppälä and Hämäläinen (2001) in different ways. Hence, instead of evaluating the summatory proposed in Eq. 1, in this paper we use **Eq. 2**, which is named Partial Indicator of impact *i* for alternative *a* [PIi(a)].

$$PIi(a) = \frac{Ni}{Ti} \cdot \frac{Ii(a)}{Ni - Ii^{TH}} \quad (2)$$

Next, the Partial Indicator (PIi(a)) is adapted to be used in the fuzzy treatment, which requires comparable values in a range between 0 and 1, where 0 is the worst and 1 the best

Table 3: Description of data sources used to get the partial indicator [PIi(a)]

Impact category (Units)	Influence area	Description of the source for normalization reference (Ni), target reference (Ti) and thresholds reference (Ii^{TH})	Values
Acidification (moles H+ equiv.)	Regional (Catalonia)	Ni = Acid emissions for Catalonia 2001 (Gencat, 2004)	1.45E+10
		Ti = Estimation for Catalonia, based on NEC's 2010 (Directive 2001/81/CE)	8.25E+09
		Ii^{TH} = Estimation of sustainable acid emissions for Catalonia, based on EEA (2002)	2.22E+09
Ecotoxicity (kg 2,4-D equiv.)	Regional (Catalonia)	Ni = Ecotoxic emissions for Catalonia in 2001 (EPER 2004)	5.43E+07
		Ti = Estimation for Catalonia 2020, based in Sea North Conference (EEA 2003)	5.43E+03
		Ii^{TH} = Estimation of sustainable ecotoxic emissions for Catalonia (EEA 2003)	0.00E+00
Eutrophication (kg N)	Local (Barcelona)	Ni = Estimation nitrates, phosphates and ammonia discharged to sea in Barcelona 2000 (EEA 2001)	2.80E+08
		Ti = Considered equal to Ni because do not exist marine eutrophication in Barcelona (EEA 2001)	2.80E+08
		Ii^{TH} = Sustainable discharges equal to zero	0.00E+00
Fossil Fuel Use (MJ)	Global	Ni = Coal, natural gas and oil consume in 2001 (EIA-DOE, 2004)	3.65E+14
		Ti = World consume projections for 2010 (EIA-DOE 2004)	4.24E+14
		Ii^{TH} = It is considered equal to the generation of fossil fuels: zero	0.00E+00
Global Warming (kg equiv CO_2)	Global	Ni = Greenhouse gas world emissions 2003 (EEA 2003)	3.21E+13
		Ti = Kyoto Protocol Target emissions 2008–2010 (Vrolijk Ch. 2002)	3.05E+13
		Ii^{TH} = Kyoto Protocol sustainable emissions, –70% GHG emissions industrialized countries (EEA 2003)	9.63E+12
Human Health Cancer (kg C6H6 equiv.)	Regional (Catalonia)	Ni = Carcinogenic emissions in Cataluña 2001 (EPER 2004)	2.03E+07
		Ti = Estimation for Catalonia 2020, based in Sea North Conference (EEA 2003)	2.03E+03
		Ii^{TH} = Zero emissions	0.00E+00
Human Health Criteria (Total DALYs)	Regional (Catalonia)	Ni = Estimation of PM10 and SO_2 emissions for Catalonia in 2000. (Parra 2004)	9.75E+06
		Ti = Estimation for Catalonia 2020, based in Sea North Conference (EEA 2003)	5.46E+06
		Ii^{TH} = Estimation of sustainable SO_2 emissions for Catalonia, based on EEA (2002)	1.76E+06
Human Health Non Cancer (kg C_7C_7 equiv.)	Regional (Catalonia)	Ni = Set of emissions that cause problems in healt (no cancer), in 2001 in Catalonia (EPER 2004)	3.27E+10
		Ti = Estimation for Catalonia 2020, based in Sea North Convention (EEA 2003)	3.27E+06
		Ii^{TH} = Zero emissions	0.00E+00
Photochemical smog (g NOx equiv.)	Regional (Catalonia)	Ni = NOx, CH_4, CO and VOC emissions in 2000 in Catalonia (Parra 2004)	2.70E+08
		Ti = Estimation for Catalonia, based on NEC's 2010 (Directive 2001/81/CE)	1.32E+08
		Ii^{TH} = Estimation of sustainable acid emissions for Catalonia, equal to 1980 emissions (EEA 2002)	4.47E+07
Water use (m^3)	Regional (Catalonia)	Ni = Water consume in Catalonia in 2002 (Cabot 2004)	1.19E+09
		Ti = Water consume proyections for 2010 in Catalonia (Cabot 2004)	1.20E+09
		Ii^{TH} = Eliminating the external contributions to diminish the deficit of water in Catalonia	9.62E+08

performance. This is somewhat akin to Hunkeler's return on Environment where a decimal scale was employed (Hunkeler and Biswas 2000). **Eq. 3** permits normalizing of PIi(a) values, to place them in the same scale and to obtain an increasing measurement of performance, consistent with the fuzzy description.

$$\overline{PIi(a)} = 1 - \frac{PI\,i(a) - PI\,i(a)_{\min}}{PI\,i(a)_{\max} - PI\,i(a)_{\min}} \tag{3}$$

2.2 Fuzzy treatment of the partial indicator

Traditional tools for formal modeling are deterministic and precise. They are based in the yes-or-no category rather than a more-or-less category. This assumes that the parameters of a model represent exactly the phenomenon modeled, which implies that the model contains no ambiguities. However, in reality imprecision exists. Zimmermann (1991) states that fuzzy set theory provides a strict mathematical framework in which imprecise phenomena can be rigorously studied. It can also be considered as a modeling language well suited to situations in which fuzzy relations and criteria exist.

Considering that estimations of emissions for all the activities in a determined area (Ni), environmental targets (Ti) and thresholds or sustainability targets (Ii^{TH}) are rarely available, and if they are they involve uncertainty, a description of the scenarios using fuzzy numbers would seem to be more realistic than with crisp numbers.

Because of that, we suggest a fuzzy treatment based on the process reported by Li and Yen (1995), which consists of associating to each normalized partial indicator a linguistic variable that describes it in semantic terms.

Fig. 1 shows the set of linguistic variables (e_k) considered E = {e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, e_9, e_{10}, e_{11}}. Here e_1 is terrible, e_2 is very, very bad, e_3 is very bad, e_4 is bad, e_5 is quite bad, e_6 is satisfactory, e_7 is quite good, e_8 is good, e_9 is very good, e_{10} is very, very good, and e_{11} is excellent.

The fuzzy measurements are defined according to the membership functions shown in **Eq. 4**, **5** and **6**, where $x = \overline{PIi(a)}$.

In order to measure the fuzzy description of the Partial Indicators, the membership function for each of the linguistic variables must be defined. For all k∈{2,3,4,5,6,7,8,9,10}, it is considered:

$$e_k(x) = \begin{cases} 0, & x \le \frac{k-2}{10}; \\ 10x - (k-2), & \frac{k-2}{10} < x \le \frac{k-1}{10}; \\ -10x + k, & \frac{k-1}{10} < x \le \frac{k}{10}; \\ 0, & x > \frac{k}{10}. \end{cases} \tag{4}$$

While, for k=1 and k=11 it is:

$$e_1(x) = \begin{cases} 1 - 10x, & 0 \le x < 0.1; \\ 0, & x \ge 0.1. \end{cases} \tag{5}$$

$$e_{11}(x) = \begin{cases} 0, & x \le 0.9; \\ 10x - 9, & 0.9 < x \le 1. \end{cases} \tag{6}$$

Considering the linguistic variables e_k (k = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11) and the impact categories I_i (i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10), for each alternative a_j (j = 1, 2, 3, 4, 5), a matrix $M_{kij} = (e_k\,(x_{ij}))$ is defined as shown in **Eq. 7**.

$$M_{kij} = \begin{pmatrix} e_1(x_{1,j}) & e_1(x_{2,j}) & e_1(x_{3,j}) & e_1(x_{4,j}) & e_1(x_{5,j}) & \cdots & e_1(x_{10,j}) \\ e_2(x_{1,j}) & e_2(x_{2,j}) & e_2(x_{3,j}) & e_2(x_{4,j}) & e_2(x_{5,j}) & \cdots & e_2(x_{10,j}) \\ e_3(x_{1,j}) & e_3(x_{2,j}) & e_3(x_{3,j}) & e_3(x_{4,j}) & e_3(x_{5,j}) & \cdots & e_3(x_{10,j}) \\ \vdots & & & & & & \\ e_{11}(x_{1,j}) & e_{11}(x_{2,j}) & e_{11}(x_{3,j}) & e_{11}(x_{4,j}) & e_{11}(x_{5,j}) & \cdots & e_{11}(x_{10,j}) \end{pmatrix} \tag{7}$$

This matrix represents the fuzzy degree of membership of each partial impact to each linguistic variable. The values of x_{ij} are calculated according to **Eq. 8**:

$$x_{ij} = \overline{PIi(a_j)} \tag{8}$$

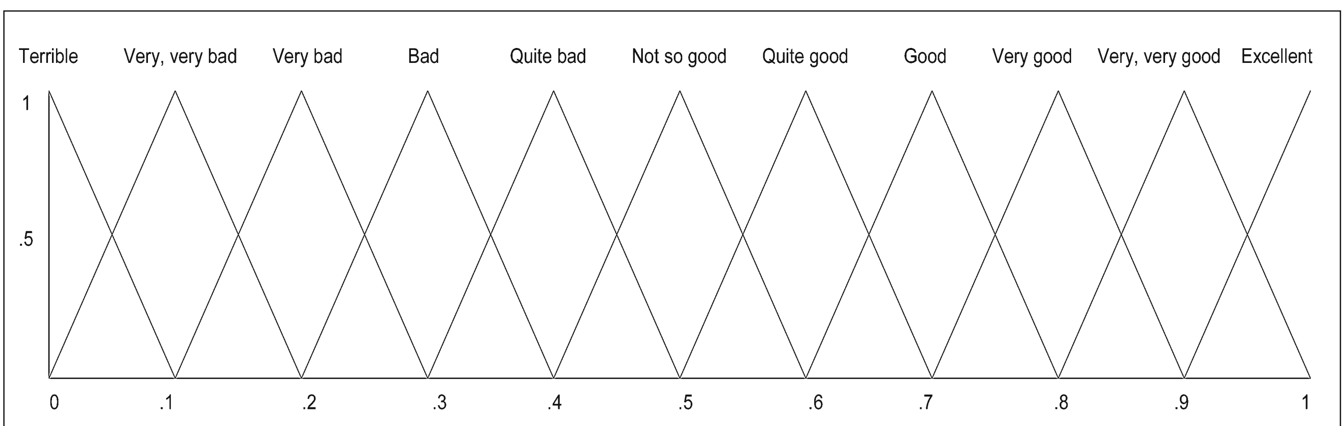

Fig. 1: Semantic scale used for the fuzzification of the Partial Indicators normalized

For each alternative, a vector containing the global membership value for each one of the linguistic labels is obtained by considering the product of matrix M_{ki} by a vector of weights $W = (w_1, w_2, \ldots, w_{10})$. Where wi are real numbers satisfying,

$$\sum_{i=1}^{10} w_i = 1$$

and defined in an elicitation process. This process correspond to the fuzzy-weighted average defined by Klir and Yuan (1995).

$$\rho^{(k)}(a_j) = M_{kij} \cdot W_i \tag{9}$$

Finally, the decision function $D(a_j)$ (**Eq. 10**) permits judgment according to the principle of maximum membership, i.e. the most realistic linguistic label is assigned to each alternative. Each scenario is assigned to the linguistic label for which it has a higher membership value.

$$D(a_j) = \max\left\{\rho^{(k_1)}(a_j), \rho^{(k_2)}(a_j), \ldots, \rho^{(kn)}(a_j)\right\} \tag{10}$$

The order defined in the set of alternatives is induced by the usual order considered in the set of fuzzy descriptions. When two alternatives are given the same label, the membership value is considered to establish an order between them.

Considering the characteristics of the decision-making process (French and Gelderman 2005), this methodology gives an iterative procedure that permits alternatives to be removed and to start again. This feature is particularly important when one of the alternatives is extremely different from the rest; in this case, the scenarios are polarized around the two extreme linguistic terms, making it difficult to distinguish a clear order of preferences. Faced with this situation, it is suggested that the most different alternative be eliminated, classifying it according to the semantic term to which it was assigned and repeating the process with the rest of the options analyzed.

3 Results

The values of the characterized impact assessment defined in Table 2 and the reference values shown in Table 3 have been considered to compute the Partial Indicators of the impact *i* for the alternative *a* [*PIi(a)*] presented in **Table 4**.

The *PIi(a)* have been normalized with the Eq. 3. The results are presented in **Table 5**.

Table 4: Partial indicators of the impact *i* for the scenario *a* [*PIi(a)*]

Alternatives (a) / Impact categories (I)	78–22 (a_1)	50–50 du (a_2)	50-50 (a_3)	67–33 (a_4)	100–0 (a_5)	Units
I_1: Acidification	3.41E+07	3.21E+07	3.39E+07	3.52E+07	3.72E+07	moles H+ equiv
I_2: Ecotoxicity	1.49E+05	2.51E+05	2.53E+05	1.95E+05	2.74E+04	kg 2,4-D equiv
I_3: Eutrophication	4.09E+04	3.88E+04	4.10E+04	4.18E+04	4.15E+04	kg N
I_4: Fossil Fuel Use	4.18E+07	4.10E+07	4.13E+07	4.18E+07	4.19E+07	MJ
I_5: Global Warming	4.90E+08	5.13E+08	5.55E+08	5.15E+08	3.48E+08	kg CO_2
I_6: Human Health Cancer	3.62E+06	6.52E+06	6.52E+06	4.89E+06	–4.06E+02	kg C_6H_6 equiv
I_7: Human Health Criteria	–6.47E+02	–1.74E+03	–1.74E+03	3.51E+01	1.57E+03	Total DALYs
I_8: Human Health Non-Cancer	4.60E+09	8.27E+09	8.27E+09	6.21E+09	3.40E+06	kg C_7H_7 equiv
I_9: Photochemical Smog	2.68E+05	1.36E+05	2.07E+05	2.75E+05	4.09E+05	gr NOx equiv
I_{10}: Water Use	8.00E+05	4.18E+05	4.34E+05	5.66E+05	8.16E+05	m^3

Note: kg 2,4-D equiv = kg of 2,4-Dichlorophenoxyacetic acid; Total DALYs = total Disability-Adjusted Life Years; t&e species = threatened and endangered species

Table 5: Partial indicators normalized, $\overline{PIi(a)}$

Scenarios / Environmental impacts	78–22	50–50 du	50–50	67–33	100–0
Acidification	4.9E-03	4.6E-03	4.9E-03	5.0E-03	5.3E-03
Ecotoxicity	2.8E+01	4.6E+01	4.7E+01	3.6E+01	5.1E+00
Eutrophication	1.5E-04	1.4E-04	1.5E-04	1.5E-04	1.5E-04
Fossil Fuel Use	9.9E-08	9.7E-08	9.7E-08	9.8E-08	9.9E-08
Global Warming	2.3E-05	2.4E-05	2.6E-05	2.4E-05	1.6E-05
Human Health Cancer	1.8E+03	3.2E+03	3.2E+03	2.4E+03	-2.0E-01
Human Health Criteria	–1.4E-04	–3.9E-04	–3.9E-04	7.8E-06	3.5E-04
Human Health Non-Cancer	7.8E+02	1.4E+03	1.4E+03	1.1E+03	5.8E-01
Photochemical Smog	2.4E-03	1.2E-03	1.9E-03	2.5E-03	3.7E-03
Water Use	3.5E-03	1.8E-03	1.9E-03	2.5E-03	3.6E-03

Table 6: Fuzzy measurements obtained for the semantic term 'Very, very bad'

Scenarios / Environmental impacts	78–22	50–50 du	50–50	67–33	100–0
Acidification	0.605	1.000	0.658	0.386	0.000
Ecotoxicity	0.459	0.010	0.000	0.256	1.000
Eutrophication	0.287	1.000	0.268	0.000	0.091
Fossil Fuel Use	0.123	1.000	0.666	0.202	0.000
Global Warming	0.314	0.204	0.000	0.195	1.000
Human Health Cancer	0.445	0.000	0.000	0.250	1.000
Human Health Criteria	0.670	0.999	1.000	0.464	0.000
Human Health Non Cancer	0.444	0.000	0.000	0.249	1.000
Photochemical Smog	0.516	1.000	0.741	0.490	0.000
Water use	0.040	1.000	0.959	0.627	0.000

Next, the fuzzy measurements are obtained scanning the $\overline{PIi(a)}$ for each one of the semantic terms considered according to the equations 4, 5 or 6. **Table 6** illustrates the results of this process for the case of the membership function of 'Very, very bad'. Here K=2, therefore Eq. 4 is used.

Considering that Finnveden et al (2002), argue that in the proposal of Seppälä and Hämäläinen (2001) an additional weighting step is needed in order to calculate the total impact, In this methodology, each fuzzy measurement is multiplied by the weight of the impact category which correspond. In this study, it has been assumed that all the impact categories have the same worth with respect to the total impact. This is in line with Chang and Yeh (2001) and with the principle of insufficient reason (Starr and Greenwood 1977), which suggest the use of equal weights when reliable subjective weights are not obtainable.

For this reason, and in order to obtain the level of membership for each of the linguistic variables considered, a vector with the inverse of the number of impact categories is used.

The values of the decision function are obtained with the summatory of all the fuzzy measurements weighted, for each scenario. **Table 7** present this values for the linguistic label 'Very, very bad'. This process is repeated for each semantic term and then a comparison is made between alternatives.

In **Table 8** the values of the decision function (see Eq. 10) are presented (in grey). As can be seen, alternatives 100–0 and 50–50 are associated with the term 'Terrible'; scenario 67–33 is related to 'Very bad'; 78–22 is linked to 'Not so good' and 50–50 du is considered 'Excellent'.

Table 7: Values of the decision function for the semantic term 'Very, very bad'

Semantic term / Scenarios	Very, very bad
78–22	0.117
50–50 du	0.010
50–50	0.000
67–33	0.005
100–0	0.091

This association is determined by the principle of gradual simultaneity (Zadeh 1965), which express that a proposition can be at one and the same time true and false, on the condition of assigning a degree to its truth and a degree to its falseness. Therefore the values of the decision function obtained represent the grade of truth which the scenarios are associated to the semantic terms.

The preferred option of the five scenarios considered is 50–50 du, because it presents the highest membership value related to the most preferable semantic term.

From Table 8, the following order of preferences in the set of alternatives can be identified: 50–50du > 78–22 > 67–33 > 50–50 > 100–0.

As a consequence of the values obtained, it can be concluded that the preferable alternative for waste management, in environmental terms, is scenario 50–50du, and the worst option is the scenario 100–0.

Table 8: Values of the decision function. The highlighted boxes show the maximum membership

Scenarios / Semantic term	78–22	50–50 du	50–50	67–33	100–0
Terrible	0.060	0.290	0.400	0.100	0.509
Very, very bad	0.117	0.010	0.000	0.005	0.091
Very bad	0.036	0.096	0.032	0.338	0.000
Bad	0.173	0.004	0.068	0.171	0.000
Quite bad	0.165	0.000	0.000	0.133	0.000
Not so good	0.232	0.000	0.000	0.154	0.000
Quite good	0.142	0.000	0.076	0.073	0.000
Good	0.074	0.000	0.183	0.027	0.000
Very good	0.000	0.000	0.041	0.000	0.000
Very, very good	0.000	0.001	0.041	0.000	0.000
Excellent	0.000	0.599	0.159	0.000	0.400

4 Discussion

4.1 The proposal methodology

The valuation is a very controversial step because the incorporation of social, political and ethical values is a difficult issue (Finnveden 1997), but this element is very important in the decision-making process (Hertwich and Hammit 2001). Therefore, it is necessary to strengthen through mechanisms that consider the subjective elements and the uncertainty in the most structured form as far as possible.

The DtT method, modified by Seppälä and Hämäläinen (2001) strengthens the normalization and weighting in LCIA, because it takes into account the emissions of all the activities for a determined area (Ni), the environmental targets (Ti) and the thresholds or sustainability targets (Ii^{TH}). However, it presents the following limitations in its practical application:

1. Not all emissions analysed have emission inventories, thus it is necessary to make some estimations.
2. If the emission inventories exist, in many cases they are defined for different periods.
3. Environmental targets are not defined in every impact category.
4. If environmental targets exist, they are defined for different periods.
5. In several cases, the targets and inventories were estimated for Catalonia based on the data for Spain.
6. The sustainability thresholds are not easy to determine, therefore they were considered as zero on some occasions.

These limitations are not only for the DtT modified by Seppälä and Hämäläinen (2001), but also for almost all valuation processes independently of the method used (Volkwein et al. 1996, Finnveden 1997, Tolle 1997, Owens 1998, Lee 1999). This situation must to be considered in LCIA because according to Ross et al. (2002), if a calculation is performed with uncertain data, and the uncertainty is disregarded, then a decision based on the calculation result may be made completely in the wrong direction.

Due to the Partial Indicator [$PI_{i(a)}$] is an uncertain value, fuzzy techniques for decision analysis provides more realistic results than traditional tools, because the fuzzy decision process proposed permits to aggregate the imprecision involved in all the $PI_{i(a)}$ and obtain a semantic label easily interpretable to each scenario separately.

The proposed methodology permits normalization and weighting in LCIA to be defined from a mathematically strengthened approach. A mathematically strengthened approach is one which the reality can be abstracted and modeled in the most precise form, in this case the fuzzy sets is a way to deal systematically with unsharp figures, which better represent the reality.

The semantic scale with eleven terms allows a gradual definition of the performance of the alternatives according to their level of membership. Bearing this in mind, it can be said that the fuzzy approach considered has assumed and admitted the uncertainty and subjectivity included in the data used.

In the methodology presented, the weights of the impact categories are considered equitable because their elicitation is a time-consuming process, and their results are not completely meaningful due to the rather low number of expert opinions on the weighting step, and the great uncertainty in the results (Seppälä 1999).

There are other papers that deal with uncertainties in input data and with the uncertainty propagation (Ciroth et al. 2004, Geisler et al. 2005, Hirokazu et al. 2005), however, in this cases it is necessarily to analyze each one of the data used in the life cycle inventory. The proposal methodology permits the making decision process considering that the results of the LCA are uncertain.

4.2 The order of preference of the scenarios of biowaste management

The order of preferences obtained indicates that the best scenario for biowaste management, in environmental terms, is 50–50 du, associated with the term 'excellent'. This is natural, because 50–50 du is the only alternative that involves direct use of biowaste, which is a set of processes that are not considered within the limits of the system analysed. It could therefore be stated that the real quantity of biowaste treated in this scenario is lower than in the other options. This alternative presents the lowest potential impacts for acidification, eutrophication, fossil fuel use, human health criteria, photochemical smog and water use. On the other hand, this scenario includes the lowest levels of composting and biogasification, and (together with the scenario 50–50) the maximum quantity of electricity exported by the system.

The scenario 78–22 is the second in order of preference, and is associated with the term 'not so good'. This alternative involves the second-lowest percentage of incineration, and presents the second-best performance in the impact categories of ecotoxicity, eutrophication, global warming, human health cancer, human health criteria and human health non-cancer.

The alternative 67–33 is related mostly to 'Very bad'. In this scenario, the quantity of biowaste that enters composting, biogasification and incineration is the same. 67–33 presents the most significant impact in eutrophication because it has the highest value of kg N equivalents emitted in this scenario, which could be due to the combination of treatments, selective collection and non-selective collection.

The option 50–50 is associated with the term 'Terrible'. This alternative considers the most important percentages of incineration, for this reason it shows the highest levels of impact in ecotoxicity, human health cancer and human health non-cancer, due to its emissions of heavy metals and dioxins; and in global warming by its carbon dioxide emissions.

The scenario 100–0 is associated with the semantic term 'Terrible' with the highest level of membership; therefore it is the worst system for biowaste management. This order of preference is coincident with the fact that 100–0 presents the worst performance in five impact categories: acidification, fossil fuel use, human health criteria, photochemical smog and water use.

The potential impacts of acidification, fossil fuel use and human health criteria are higher, due to the increase in selective collection. According to Baldasano et al. (2002), this is a process where the yields decrease, since there is a lower compacting of the fermentable fraction in the collecting trucks in order to avoid the production of leachates and the later processes of biologic fermentation. This involves more routes, therefore more fossil fuel use, higher formation of nitrogen dioxide that contributes to the acidification, and more PM_{10} emissions, impacting significantly in the category of human health criteria.

The formation of photochemical smog is an impact category in which the processes of compost manufacturing are determinant. This is caused mainly by VOC emissions, which are substantially increased in scenario 100–0.

The impact on water use in 100–0 is determined by biogasification process, because the technology used (Linde KCA Humid) requires greater quantities of water (7.6 m^3 per ton of biowaste treated (AMR 1997)).

5 Conclusions

In order to obtain an effective helping tool in the decision-making process for LCA, it seems necessary to strengthen the valuation element through mechanisms that consider the inexact and subjective elements in the most structured way possible.

The use of the Eq. of DtT, modified according to MAVT, provides a theoretical support in the process of normalization and valuation. Nevertheless, it has limitations related to the availability and reliability of information.

The proposed methodology permits the decision analysis considering the uncertainty involved in the LCIA results by means of the fuzzy sets theory.

According to the proposed methodology, the best alternative for biowaste management is 50–50 du, which includes direct use of the biowaste not considered within the analysis, and the worst scenario is 100–0, which in spite of considering only biological treatment for biowaste, generates the highest impacts related to the yield of selective collection, emissions in composting and water use in biogasification.

6 Recommendations and Perspectives

The order of preferences obtained agrees with expert opinion and is consistent with the characteristics of each of the scenarios analyzed. However it is necessary to apply this methodology to other situations in order to analyze its functionality, and to compare the process defined with other fuzzy approaches, which could be appropriate for the valuation step in LCA.

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