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Waste treatment: an environmental, economic and social analysis with a new group fuzzy PROMETHEE approach

Francesco Lolli[1], *Alessio Ishizaka*[2*], *Rita Gamberini*[1], *Bianca Rimini*[1], *Anna Maria Ferrari*[1], *Simona Marinelli*[3], *Roberto Savazza*[1]

[1]*Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia*, Via Amendola 2, Padiglione Morselli, 42122 Reggio Emilia, Italy

[2]*Centre for Operational Research and Logistics, Portsmouth Business School, University of Portsmouth*, Portland Street – Richmond Building, Portsmouth PO1 3DE, United Kingdom

[3]*Department of Civil Buildings Engineering and Architecture, Università Politecnica delle Marche*, Via Brecce Bianche 12, 60131 Ancona, Italy

Abstract

Most complex decisions involve several stakeholders and therefore need to be solved using a group multi-criteria decision method. However, stakeholders or decision-makers often have divergent views, especially in the environmental sector. In order to integrate this divergence, a new group fuzzy PROMETHEE approach is introduced to combine the traditional environmental criteria of Life Cycle Assessments (LCA) with social and economic criteria. The modelling of uncertainty within the group of decision-makers using a fuzzy approach makes this method unique. The proposed fuzzy approach differs significantly from the standard one. The decision-makers express their judgments in crisp forms. In order to take into account the intrinsic dispersion of judgments within the group, a posteriori fuzzification procedure is applied. The crisp values are not simply aggregated; they are converted into a triangular fuzzy number based on the given evaluations. As a consequence, the definition of fuzzy membership functions, as required in standard fuzzy logic, is not required, which simplifies the process and makes it more reliable.

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[*] Corresponding author: Prof. Alessio Ishizaka
E-mail: Alessio.Ishizaka@port.ac.uk
Tel.: +44 2392844171

The new approach is illustrated with a real case study concerning the selection of the best waste treatment solution in a natural park from among a traditional incinerator and an innovative integrated plant.

Keywords: Waste treatment, multi-criteria decision analysis, fuzzy theory, PROMETHEE, group decision

1. Introduction and research background

Municipal Solid Waste Management (MSWM) represents a complex system involving technical, environmental, social and economic criteria with potentially serious effects on communities if not managed correctly. The technical perspectives and solutions have attracted the interest of researchers and practitioners for decades. Different typologies of waste, as well as technologies and solutions for managing them, have been explored. For instance, the recovery of electric and electronic equipment has been discussed in terms of both network design (Gamberini et al. 2008), and technical solutions for collection and transport (Gamberini et al. 2009). Solid waste composting has been analogously analysed through different technical perspectives, from selecting the best composter model in terms of physico-chemical indicators (Kumar et al. 2009), to introducing engineering indexes (Gamberini et al. 2013a) and comparing different plants (Gamberini et al. 2013b) for solid waste composting.

With regard to the environmental criterion of sustainability, it has been widely recognised that LCAs are a powerful decision aid for MSWM, and in particular for waste treatment (Soltani et al. 2015). LCAs consist of a quantitative approach for assessing the environmental impact 'from cradle to grave' of either a process or a product along certain quantifiable environmental categories by means of a multi-scenario analysis. The number of LCA studies proposed on waste treatment confirms this remark, especially in the case of new treatment technologies or specific typologies of waste to treat. By way of example, some recent contributions to this research field are reported below. An LCA model for waste incineration coupled with new technologies to recover metals from combustion residues has been developed by Boesch et al. (2014). The organic fibre produced by autoclaving unsorted municipal solid waste has been treated by Quirós et al. (2014) using a multi-scenario LCA approach. A multi-scenario LCA has also been conducted by Erses Yay (2015), where incineration, composting, a material recovery facility and landfilling are combined in different municipal solid waste treatment scenarios and then compared by means of an LCA methodology. Vázquez-Rowe et al. (2015) have compared five different treatment systems for digestate using LCAs. Di Gianfilippo et al. (2015) have dealt with the bottom ash generated from two thermal treatment solutions (incineration and gasification), and managed by means of two different options: landfilling and recycling. An LCA methodology is used again to compare the different scenarios from an environmental viewpoint. The bottom ash generated by incineration has also been analysed by Margallo et al. (2014), who applied an LCA methodology to evaluate and compare the environmental impacts of ash solidification and ash recycling. A recent review (Margallo et al. 2015) aims to examine the impact on the environment of management and reuse options for municipal solid wastes with a life cycle assessment. Readers can refer to Laurent et al. (2014a) for other contributions on the application of LCA methodologies to waste treatment.

Nevertheless, as already underlined, the sustainability of complex systems like waste treatment should not only consider environmental goals. An increasing need for integrative approaches in line with the total quality management philosophy has arisen in all mature production and service fields. Therefore, LCAs should be integrated into economic and social assessments, respectively named life cycle costing (LCC) and social life cycle assessment (SLCA), in order to assess the global impact of the production/service systems under analysis. Such a need was underlined early on by Klöpffer (2008), and then formalised as a life cycle sustainability assessment (LCSA) in UNEP/SETAC (2011). Consequently, three pillars of the sustainability concept emerge: the environmental, economic and social goals, referred to by Sikdar (2007) as the triple bottom line. This holistic perspective represents a relevant trend in the literature on sustainability, leading to different approaches of 'systems thinking' during the last decade, for instance Fiksel et al. (2014).

In particular, LCCs represent a method for assessing the total cost of facility ownership taking into account all the costs of acquiring, owning and disposing of a system. When selecting an alternative to maximise the net savings, LCCs are especially important where projects differ in their initial and operating costs. For an early discussion on the theory and practice of LCCs, readers can refer to Cole and Sterner (2000). LCCs have a much longer history than LCAs, which were actually designed to deal with the same problem from a different perspective. Hence, their purposes and methodological approaches differ substantially (Rebitzer and Hunkeler 2003). Their comparison and integration have been extensively tackled in the last decade; see for instance the early contributions of Norris (2001).

With regard to SLCAs, UNEP/SETAC (2009) classifies the social stakeholders into five categories (workers, local community, society, consumers and value chain actors), which can have an impact on six social categories (human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions), whose subcategories are characterised by more than one hundred indicators (UNEP/SETAC 2013). Readers can refer to the recent review on 'socialising' sustainability by Chhipi-Shrestha et al. (2015), and Hauschild et al. (2008) as an example of an integrative approach of LCAs and SLCAs.

The conceptual formula LCSA=LCA+LCC+SLCA maintains its relevance a fortiori in the MSWM field due to the heterogeneity of the stakeholders involved. Therefore, in this paper, the technical dimension of MSWM is solved by selecting a waste treatment plant according to its environmental, social and economic sustainability impact. MSWM has a multi-dimensional nature and needs to achieve different goals that satisfy several stakeholders, such as government, municipalities, citizens, industries, environmentalists, etc. Therefore, a group multi-criteria decision method for MSWM is needed. Recently, the field of multi-criteria decision analysis (MCDA) has demonstrated its effectiveness in MSWM as a consequence of this kind of integrative perspective, in terms of both criteria and decision-makers. MCDA is therefore a powerful tool for integrating all the aspects of LCSAs (El-Hanandeh and El-Zein 2010), by dealing with some quantitative criteria as impact categories of LCAs and LCCs, along with some qualitative criteria, which is typically the case for SLCAs. Therefore, MCDA allows more robust decisions to be reached than purely cost and environment-based approaches, leading to a more enriched comparison of alternatives.

The application of MCDA is not new in MSWM in general, as well as specifically in the field of waste treatment research. To the best of our knowledge, the first review on MCDA for MSWM was proposed by Morrissey and Browne (2004), who stated that no model examined up to 2004 had considered all three aspects together. However after more than a decade, this statement has to be necessarily reviewed. Readers can refer to the more recent reviews by Achillas et al. (2013) on the application of MCDA in MSWM, Soltani et al. (2015) for a focus on group MCDA for MSWM, and Herva and Roca (2013) on the applications of MCDA to environmental sciences in general. AHP (Saaty 1980), PROMETHEE (Brans 1982) and TOPSIS (Hwang and Yoon 1981) represent only a sample of MCDA methods used in MSWM. It is worth mentioning that each method shows a specific ranking model in accordance with a logic which is more or less suitable to the specifics of the multi-criteria problem concerned, such as the availability and typology of data to be managed. Only considering the waste treatment strategy using multiple decision-maker MCDA methods, Soltani et al. (2015) select thirty-one contributions from 1991 to 2013, the majority of which use the AHP and then the PROMETHEE methods. They consider the environmental, economic and social pillars but do not go into details concerning the LCAs, LCCs and SLCAs. Furthermore, Soltani et al. (2015) reviewed a relevant quantity of AHP-based contributions that were empowered to work

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with the fuzzy logic developed by Zadeh (1965). This is a well-established method in MCDA literature for representing the judgments of a decision-maker when assigning the evaluations and weights of criteria given instances of uncertainty and vagueness, as well as the variability of data. Readers can refer to Mardani et al. (2015) for a review of fuzzy logic. This approach requires linguistic judgments to be converted into fuzzy numbers defined by membership functions.

The uncertainty inherent in the multi-dimensional sustainability concept has been tackled by Dorini et al. (2011), who considered uncertainty in input variables and the preference of decision-makers by means of a probabilistic approach coupled with a Monte Carlo pseudo-random generation. The model was validated based on a case study referring to the generation of electricity from coal and biomass. Vinodh (2011) introduced a sustainability assessment approach alongside environmental, economic and social dimensions by adopting a fuzzy approach both for weighting the criteria and for assigning scores to the alternatives. However, he does not use the precision of LCAs, LCCs and SLCAs. Moreover, the application of this model does not refer to MSWM. For a recent contribution on sustainable MSWM in fuzzy environments, readers can refer to Liu et al. (2015), where the performance of the alternatives for the criteria are expressed as fuzzy numbers.

The variability of data as a source of uncertainty in LCAs, especially in the life cycle inventory analysis, has been also tackled with the possibility theory by Tan et al. (2002, 2004), and with the fuzzy theory (Tan 2008). Furthermore, fuzzy linear programming has been used by Tan (2005) and Tan et al. (2008) to handle the issue of comparing different options though LCAs because of potential conflicting goals. However, the membership function definition is one of the major concerns of fuzzy logic, although it is often not explained (Ishizaka and Nguyen 2013).

In this paper, a new fuzzy approach, which significantly differs from the standard approach, is introduced to solve this issue. In fact, the decision-makers express their judgments in crisp forms, both for the weights of criteria, and for the scores of alternatives for qualitative criteria. Each decision-maker may have very different evaluations. In order to take into account such an intrinsic dispersion of judgements within the group, a posteriori fuzzification procedure is then applied. The crisp values are not simply aggregated; they are converted into a triangular fuzzy number bounded by the minimum and maximum values assigned by decision-makers, so that the fuzzy membership function is endogenously constructed. It follows that this new approach appears more robust, as well as automatable in practical settings. Overall, this approach is completely different from the mapping of judgmental uncertainty for a single decision-maker provided by standard fuzzy logic approaches. Uncertainty is now due to divergence within the group of decision-makers instead of judgemental vagueness. That is to say, the uncertainty is generated by the different decision-makers or stakeholders.

In this study, a method from the PROMETHEE family has been preferred because it requires less information from the decision-makers than AHP, especially when the problem is large. Furthermore, the choice of a PROMETHEE-based method has been driven by some of the advantages it offers: the high level of flexibility when defining preference/indifference thresholds for criteria and the ability to incorporate qualitative and quantitative criteria without requiring any kind of normalisation approach (Ishizaka and Nemery 2011). These advantages justify the use of a group PROMETHEE-based method for solving the case study of this paper.
The new group fuzzy PROMETHEE introduced here has been applied to the selection of the best waste treatment solution, which is the core topic of MSWM (Soltani et al. 2015). In particular, alternative waste treatment solutions in a natural park area are compared by integrating economic and social criteria into the life cycle assessment (LCA).

The paper is organised as follows: the steps of the proposed method are detailed in section 2, section 3 describes the case study from data collection to the application of the new method, and finally, section 4 contains conclusions and managerial insights.

Notation

I = number of alternatives

M = number of decision-makers

J = number of leave criteria

R = number of criteria

J^O = set of quantitative (i.e. objective) leave criteria

J^S = set of qualitative (i.e. subjective) leave criteria

J = set of leave criteria where $J = J^O \cup J^S$, with $J^O \cap J^S = \emptyset$

a_i = alternative, where $i = 1, \dots, I$

d_m = decision-maker, where $m = 1, \dots, M$

c_j = leave criterion, where $j = 1, \dots, J$

l_j = level of c_j in the hierarchy, where $j = 1, \dots, J$

c_r = criterion, where $r = 1, \dots, R$

$\Gamma(c_r) = \{\text{sub-criteria of } c_r\}$, where $r = 1, \dots, R$

$w_{m,r}$ = weight assigned to c_r by d_m, where $r = 1, \dots, R$ and $m = 1, \dots, M$

$w_{m,j}$ = weight assigned to c_j by d_m, where $j = 1, \dots, J$ and $m = 1, \dots, M$

$x_{i,j}$ = value of alternative a_i for the criterion c_j, where $i = 1, \dots, I$ and $c_j \in J^O$

$x_{m,i,j}$ = value of alternative a_i for the criterion c_j given by decision-maker d_m, where $i = 1, \dots, I$, $c_j \in J^S$, and $m = 1, \dots, M$.

2. The hierarchical fuzzy group PROMETHEE

A problem can be modelled using a multi-level hierarchy composed of the goal at the root (level 1), criteria, sub-criteria and alternatives on successive levels. The alternatives represent the leaves of the hierarchy. In the following, the term ‘leaves criteria’ indicates those elements at the penultimate level of the hierarchy.

The steps of the hierarchical fuzzy group PROMETHEE are explained in the following.

Step 1: Assignment of the fuzzy weights to criteria.

Each decision-maker d_m assigns weights to each criterion c_r, where $r = 1, \dots, R$, with respect to their parents at the upper level. At level 2, criteria are compared with respect to the goal. The root at level 1 is assigned a unitary weight. The normalisation condition is imposed on each sibling:

$$\sum_{c_k \in \Gamma(c_r)} \boldsymbol{w_{m,k}} = \boldsymbol{w_{m,r}} \qquad \forall \boldsymbol{r} = \boldsymbol{1}, \dots, \boldsymbol{R}, \text{ and } \forall \boldsymbol{m} = \boldsymbol{1}, \dots, \boldsymbol{M} \tag{1}$$

Eq. (2) gives the mean weight of the criteria by aggregating the evaluation of all M decision-makers:

$$\boldsymbol{w_j} = \frac{\boldsymbol{1}}{\boldsymbol{M}} \sum_{\boldsymbol{m}=\boldsymbol{1}}^{\boldsymbol{M}} \boldsymbol{w_{m,r}} \qquad \forall \boldsymbol{r} = \boldsymbol{1}, \dots, \boldsymbol{R}, \tag{2}$$

However, eq. (2) does not take into account the dispersion of the judgments around the mean value w_j. Hence, a triangular fuzzy number is achieved for each criterion as follows:

$$\boldsymbol{\tilde{w}_j} = \left(\boldsymbol{lw_j}, \boldsymbol{mw_j}, \boldsymbol{uw_j}\right) = (\min_{\boldsymbol{m}=\boldsymbol{1},\dots,\boldsymbol{M}} \{\boldsymbol{w_{m,j}}\}, \boldsymbol{w_j}, \max_{\boldsymbol{m}=\boldsymbol{1},\dots,\boldsymbol{M}} \{\boldsymbol{w_{m,j}}\} \tag{3}$$

where the lower and upper bounds are respectively given by the lowest and highest weights assigned by the decision-makers to the criterion *j*.

Step 2: Fuzzy decision matrix.

Each decision-maker d_m expresses his own score $x_{m,i,j}$ for each alternative a_i for the qualitative criteria $c_j \in J^S$.

The fuzzy score of a_i on $c_j \in J^S$ is given as:

$$\boldsymbol{\tilde{x}_{i,j} = \left(lx_{i,j}, mx_{i,j}, ux_{i,j}\right) = (\min_{m=1,\dots,M}\{x_{m,i,j}\}, \frac{1}{M}\sum_{m=1}^{M} x_{m,i,j}, \max_{m=1,\dots,M}\{x_{m,i,j}\})} \quad (4)$$

If the criterion is quantitative, it does not need to give another value score. The crisp score $x_{i,j}$ is used as $\tilde{x}_{i,j} = (x_{i,j}, x_{i,j}, x_{i,j})$ in the performance matrix.

A fuzzy performance matrix is thus given as:

$$\boldsymbol{\tilde{D} = \left[\tilde{x}_{i,j}\right]_{I\times J} = \begin{bmatrix} \tilde{x}_{1,1} & \dots & \tilde{x}_{1,J} \\ \dots & \dots & \dots \\ \tilde{x}_{I,1} & \dots & \tilde{x}_{I,J} \end{bmatrix}} \quad (5)$$

Step 3: Fuzzy indifference and preference thresholds.

Preference functions $P_j(a_i, a_{i'})$ between two alternatives a_i and $a_{i'}$ for criterion c_j are defined by the indifference and preference thresholds (Brans and Vincke 1985). Such a preference function allows the difference between a_i and $a_{i'}$ for c_j to be converted into a preference degree in the $[0-1]$ range.

As for the weights (Step 1) and performances (Step 2), decision-makers may express different thresholds. In order to take into account the divergence of opinions of the decision-makers, a fuzzy number is constructed:

Indifference threshold:

$$\boldsymbol{\tilde{q}_j = \left(lq_j, mq_j, uq_j\right) = (\min_{m=1,\dots,M} q_{m,j}, \frac{1}{M}\sum_{m=1}^{M} q_{m,j}, \max_{m=1,\dots,M} q_{m,j}) \quad j = 1, \dots, J} \quad (6)$$

Preference threshold:

$$\boldsymbol{\tilde{p}_j = \left(lp_j, mp_j, up_j\right) = (\min_{m=1,\dots,M} p_{m,j}, \frac{1}{M}\sum_{m=1}^{M} p_{m,j}, \max_{m=1,\dots,M} p_{m,j}) \quad j = 1, \dots, J} \quad (7)$$

The spread of the fuzzy numbers again represents the level of discordance among decision-makers.

Step 4: Fuzzy preference function.

As the indifference and preference thresholds are fuzzy, the preference function is consequently also fuzzy: $\tilde{P}_j(\tilde{x}_{i,j}, \tilde{x}_{i',j}) = (lP_{ii',j}, mP_{ii',j}, uP_{ii',j})$, where $lP_{ii',j}$, $mP_{ii',j}$, and $uP_{ii',j}$ respectively represent the lower bound, the modal and the upper bound of the preference degree between a_i and $a_{i'}$ for c_j, where $i \neq i'$. If $i = i'$, then $lP_{ii',j} = mP_{ii',j} = uP_{ii',j} = 0$.

A linear non-decreasing fuzzy preference function is assumed.

In order to calculate the lower preference bound $lP_{ii',j}$, the lower preference function that gives the lowest preference degree for fuzzy indifference (Eq. 6) and preference (Eq. 7) thresholds needs to be constructed. Therefore, the upper indifference uq_j and upper preference up_j thresholds need to be used for this purpose (Figure 1). Without loss of generality, only benefit criteria (that maximise) are considered in the following.

The lower bound preference degree is given as:

$$\boldsymbol{lP_{ii',j}} = \begin{cases} \mathbf{0} & \text{if } \boldsymbol{min}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} \leq \boldsymbol{uq_j} \\ \frac{(\boldsymbol{min}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} - \boldsymbol{uq_j}}{\boldsymbol{up_j} - \boldsymbol{uq_j}} & \boldsymbol{otherwise} \\ \mathbf{1} & \text{if } \boldsymbol{min}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} \geq \boldsymbol{up_j} \end{cases} \quad (8)$$

To calculate the modal preference degree $mP_{ii',j}$, the modal preference function is constructed with the modal indifference mq_j (Eq. 6) and preference mp_j (Eq. 7) thresholds. The modal preference degree is given as:

$$\boldsymbol{mP_{ii',j}} = \begin{cases} \mathbf{0} & \text{if } \boldsymbol{mx_{i,j}} - \boldsymbol{mx_{i',j}} \leq \boldsymbol{mq_j} \\ \frac{(\boldsymbol{mx_{i,j}} - \boldsymbol{mx_{i',j}}) - \boldsymbol{mq_j}}{\boldsymbol{mp_j} - \boldsymbol{mq_j}} & \boldsymbol{otherwise} \\ \mathbf{1} & \text{if } \boldsymbol{mx_{i,j}} - \boldsymbol{mx_{i',j}} \geq \boldsymbol{mp_j} \end{cases} \quad (9)$$

In order to calculate the upper bound $uP_{ii',j}$, the upper preference function that gives the highest preference degrees needs to be constructed with the fuzzy indifference (Eq. 6) and preference (Eq. 7) thresholds. Therefore, the lower indifference lq_j and lower preference lp_j thresholds need to be used. The upper bound preference degree is given as:

$$\boldsymbol{uP_{ii',j}} = \begin{cases} \mathbf{0} & \text{if } \boldsymbol{max}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} \leq \boldsymbol{lq_j} \\ \frac{\boldsymbol{max}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} - \boldsymbol{lq_j}}{\boldsymbol{lp_j} - \boldsymbol{lq_j}} & \boldsymbol{otherwise} \\ \mathbf{1} & \text{if } \boldsymbol{max}\{(\boldsymbol{ux_{i,j}} - \boldsymbol{lx_{i',j}}); (\boldsymbol{lx_{i,j}} - \boldsymbol{ux_{i',j}})\} \geq \boldsymbol{lp_j} \end{cases} \quad (10)$$

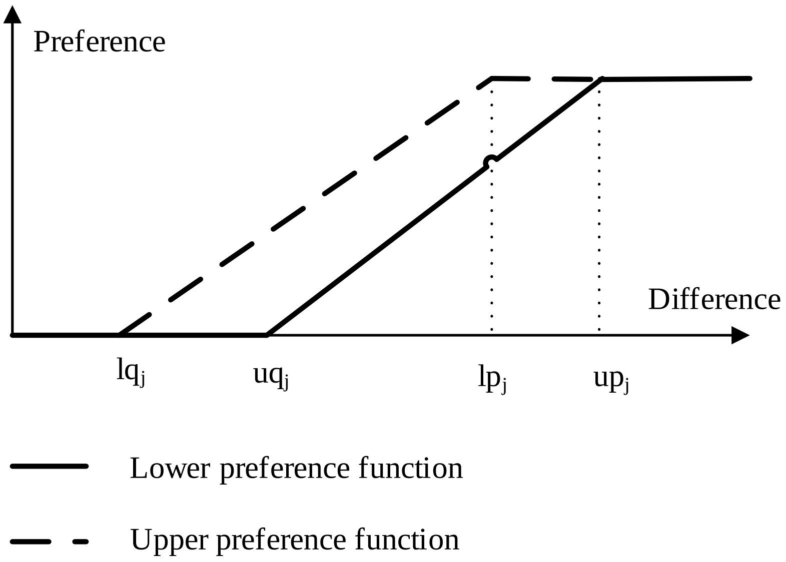

Figure 1: Lower and upper preference functions

Step 5: Fuzzy flows.

Two fuzzy flows are calculated. The former is named 'leaving flow' $\tilde{\phi}_i^+$ and indicates the overall (i.e. aggregated for all criteria) preference degree of a_i over the other alternatives. The latter is named 'entering flow' $\tilde{\phi}_i^-$ and indicates the overall preference degree of the alternatives over a_i. They are respectively calculated as follows:

$$\tilde{\boldsymbol{\phi}}_i^+ = (\boldsymbol{l\phi}_i^+, \boldsymbol{m\phi}_i^+, \boldsymbol{u\phi}_i^+) = \sum_{i'}^{I} \frac{\sum_{j=1}^{J} \tilde{w}_j (\times) \tilde{P}_j\left(\tilde{x}_{i,j}, \tilde{x}_{i',j}\right)}{n-1} \qquad \boldsymbol{i, i' = 1, .., I;\ j = 1, \dots, J} \tag{11}$$

$$\tilde{\boldsymbol{\phi}}_i^- = (\boldsymbol{l\phi}_i^-, \boldsymbol{m\phi}_i^-, \boldsymbol{u\phi}_i^-) = \sum_{i'}^{I} \frac{\sum_{j=1}^{J} \tilde{w}_j (\times) \tilde{P}_j\left(\tilde{x}_{i',j}, \tilde{x}_{i,j}\right)}{n-1} \qquad \boldsymbol{i, i' = 1, .., I;\ j = 1, \dots, J} \tag{12}$$

Their difference gives the net flow:

$$\tilde{\boldsymbol{\phi}}_i^{net} = (\boldsymbol{l\phi}_i^{net}, \boldsymbol{m\phi}_i^{net}, \boldsymbol{u\phi}_i^{net}) = \tilde{\boldsymbol{\phi}}_i^+ (-) \tilde{\boldsymbol{\phi}}_i^- \qquad \boldsymbol{i = 1, .., I,} \tag{13}$$

which is also a fuzzy number.

Step 6: Defuzzification.

This step aims to convert the fuzzy net flows calculated in step 5 into crisp values. Popular defuzzification approaches include the weighted average method, the centroid method, the mean-max membership, the centre of sums, the max-membership principle and the first (or last) of maxima. The most common approach is the centre of area or centroid method (Ordoobadi 2009). For a triangular fuzzy number, the centre of area is calculated as:

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$$\boldsymbol{\phi_i^{net} = (l\phi_i^{net} + m\phi_i^{net} + u\phi_i^{net})/3} \qquad \boldsymbol{i = 1,..,I} \qquad (14)$$

The higher ϕ_i^{net}, the more preferable the alternative a_i.

3. Case study: waste treatment in a natural park area.

This study refers to a cluster of municipalities in the Sila Park, a natural area in the south of Italy. It extends for 73,695 ha and covers twenty-one municipalities distributed over three districts. In particular, the dataset comes from a representative sample of eleven municipalities inside the Province of Cosenza. The first goal of this project was to create an environmental LCA comparison between the current waste treatment solution consisting of an incinerator plant, and the innovative integrated plant proposed by Milani et al. (2014). The waste treatment solution is then provided via two alternative waste collection modes: the former is performed by a private company already operating in the Sila Park area, whilst the latter involves a cooperative operating in the social rehabilitation field. Finally, the integrated plant is designed to work with three sorting waste collection percentages 40%, 50% and 60%, higher than the current one (18%). Ten different scenarios, named s1 to s10, are generated and evaluated with the revised group fuzzy PROMETHEE. They are summarised in Table 1, where their variable features are the waste treatment strategy (WT), the percentage of sorted waste collection (%SC) and the type of company engaged in the collection service (C).

	WT		%SC				C	
Scenario	*Incinerator*	*Integrated*	*Current*	*40%*	*50%*	*60%*	*Private*	*Cooperative*
s1	x		x				x	
s2		x	x				x	
s3	x		x					x
s4		x	x					x
s5		x		x			x	
s6		x		x				x
s7		x			x		x	
s8		x			x			x
s9		x				x	x	
s10		x				x		x

Table 1. The ten scenarios under analysis.

The two waste treatment strategies are briefly explained in Section 4.1. The criteria adopted to evaluate the strategies are presented in Section 4.2 and the evaluation is presented step-by-step in Section 4.3.

3.1 Waste treatment strategies

Traditional incineration

Good quality materials obtained via a sorted waste collection are directed by recycling processes in accordance with EU guidelines and with the aim of limiting the need for virgin materials in production processes. Unsorted waste components, along with impurities and fractions, are not included in the recovery process and are sent to incineration.

Figure 2 shows the flow chart for waste treatment by traditional incineration. The first process analysed is the kerbside collection in which all process energies, transport and impacts related to the production of bags and bins are calculated. An unsorted waste fraction sent to the incineration plant and a sorted fraction are obtained from the collection. The incineration process of the unsorted fraction will not be studied in the following, since it does not represent a differential process with respect to the innovative option described in the next paragraph. This study will concentrate on the processes of separating and screening sorted waste, identifying good quality materials to send to the recycling processes. The recycling of wood, paper, plastic, glass and metals is a non-differential process and disregarded in the rest of the work. Special attention will be paid to all impurities arising from the non-recoverable screening and a selection of sorted waste (the organic fraction and green waste). It can be seen in Figure 2 that they are directed to the incineration process, which will be studied in terms of required resources and emissions produced, in addition to electrical and thermal energy produced, in the quantities provided by the database, allocated as saved products. An alternative waste treatment is explained in the following paragraph.

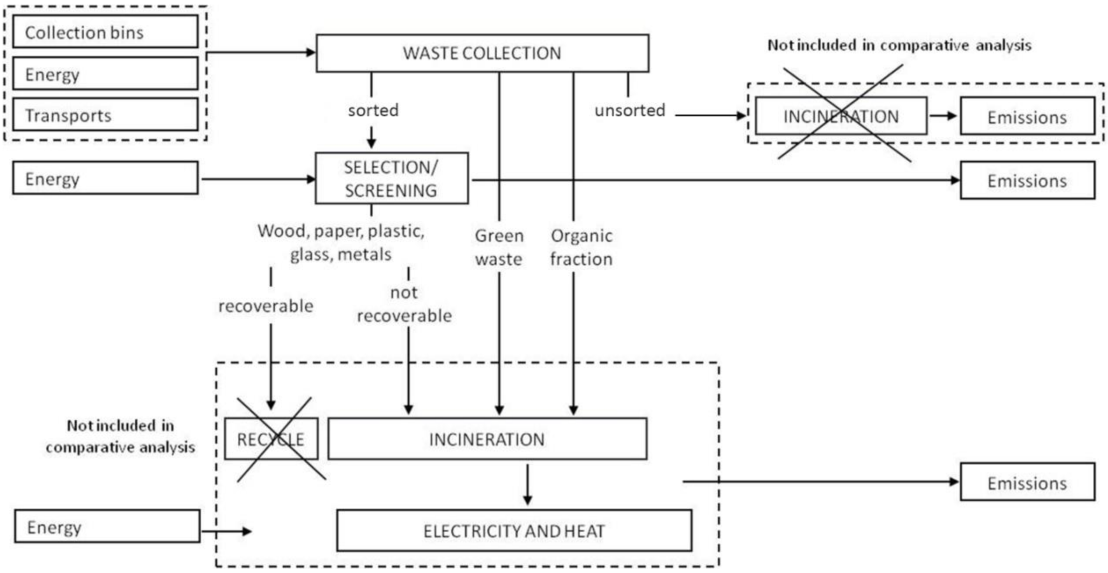

Figure 2. Flow chart of main processes for incineration.

An innovative integrated plant

This plant has been proposed by Milani et al. (2014). Incineration is reserved only for the unsorted fraction of waste without considering recyclable impurities. All the remaining components are treated using an innovative integrated system. The organic waste undergoes decomposition under anaerobic digestion (wet mesophilic technology) conditions in order to produce biogas. In particular, the optimal condition of the mixture input is obtained by the addition of water. The varying composition of waste in different seasons of the year results in a different input and subsequently changes the levels of water consumption. However, in this study, these seasonal variations were not analysed; an annual average value is considered. The green waste undergoes a drying process, after which it is treated by gasification inside a downdraft gasifier. The remaining components, which are not directly included in a recycling process (i.e. non-recoverable plastic, paper and wood), are treated with gasification and produce syngas. Biogas and syngas are used to produce electrical energy and heat in a cogeneration system. Part of this energy is used directly by the plant and the remaining part is available for external uses. The innovative plant includes another step: the digested waste passes through a fluid-solid separator which divides the solid part (which enters the gasifier process) from the liquid part, used for the production of demineralised water via nanofilter and reverse osmosis processes. Regarding the waste plant, dust retained by the filters and residues from the digestion processes, gasification and nanofiltration are sent to landfill. Figure 3 shows the flow chart of the innovative integrated plant.

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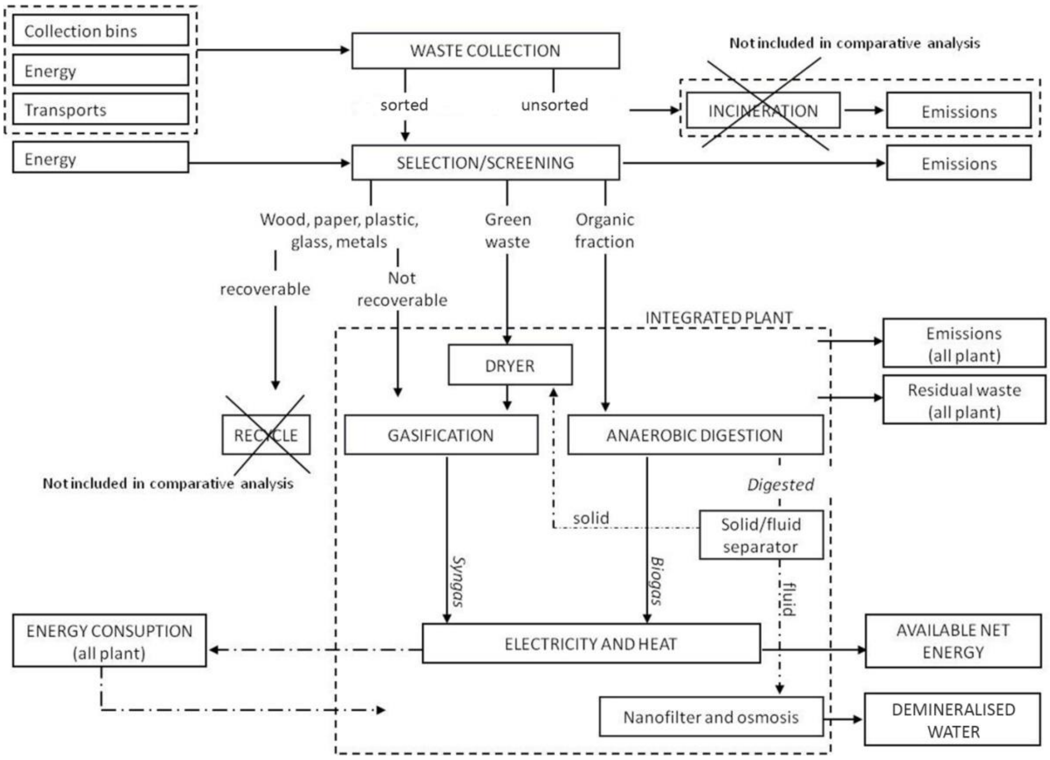

Figure 3. Flow chart of the main processes in the integrated plant.

3.2 Criteria assessment

Based on the LCAs, LCCs and SLCAs, twenty-one criteria are selected (see Figure 4). In particular, the LCA has been conducted according to the methodology indicated by international standards (ISO 14040 and ISO 14044) and the recommendations of the Joint Research Centre guidelines (EUR 23021 EN, EUR 23021 EN/2). The analysis was performed using SimaPro 7.3.3 software, taking the Ecoinvent database (Swiss Centre for Life-Cycle Inventories 2009) as reference to configure the inventory of processes. The life cycle impact assessment (LCIA) results are generated using the IMPACT2002+ method (Jolliet et al. 2003). They determine the environmental impacts related to the emissions released and resources consumed in the system under consideration. As predicted, all criteria referred to in the LCA (environmental criteria in Figure 4) are quantitative and of cost-type, i.e. to minimise.

The economic criterion adopted in this work is the Net Present Value (NPV), calculated by comparing the balance of positive and negative cash flows. This is a benefit-type criterion, i.e. to maximise, and typically objective. Due to data privacy, the values for this monetary criterion are converted into unitless scores on a scale of 1 to 20.

The social dimension is evaluated along with three qualitative criteria again with scores on a scale of 1 to 100. The first is 'work acceptability' and refers to the expected level of worker acceptance of work conditions including safety, remuneration and atmosphere in the workplace. The second criterion is 'social acceptability', and concerns citizens’ perception of waste treatment solutions in terms of noise, smell, risks, opportunities for the community and so on. Finally, the third criterion is 'job creation', which represents the employment opportunities offered by the various waste treatment solutions. All of these social criteria are to be maximised.

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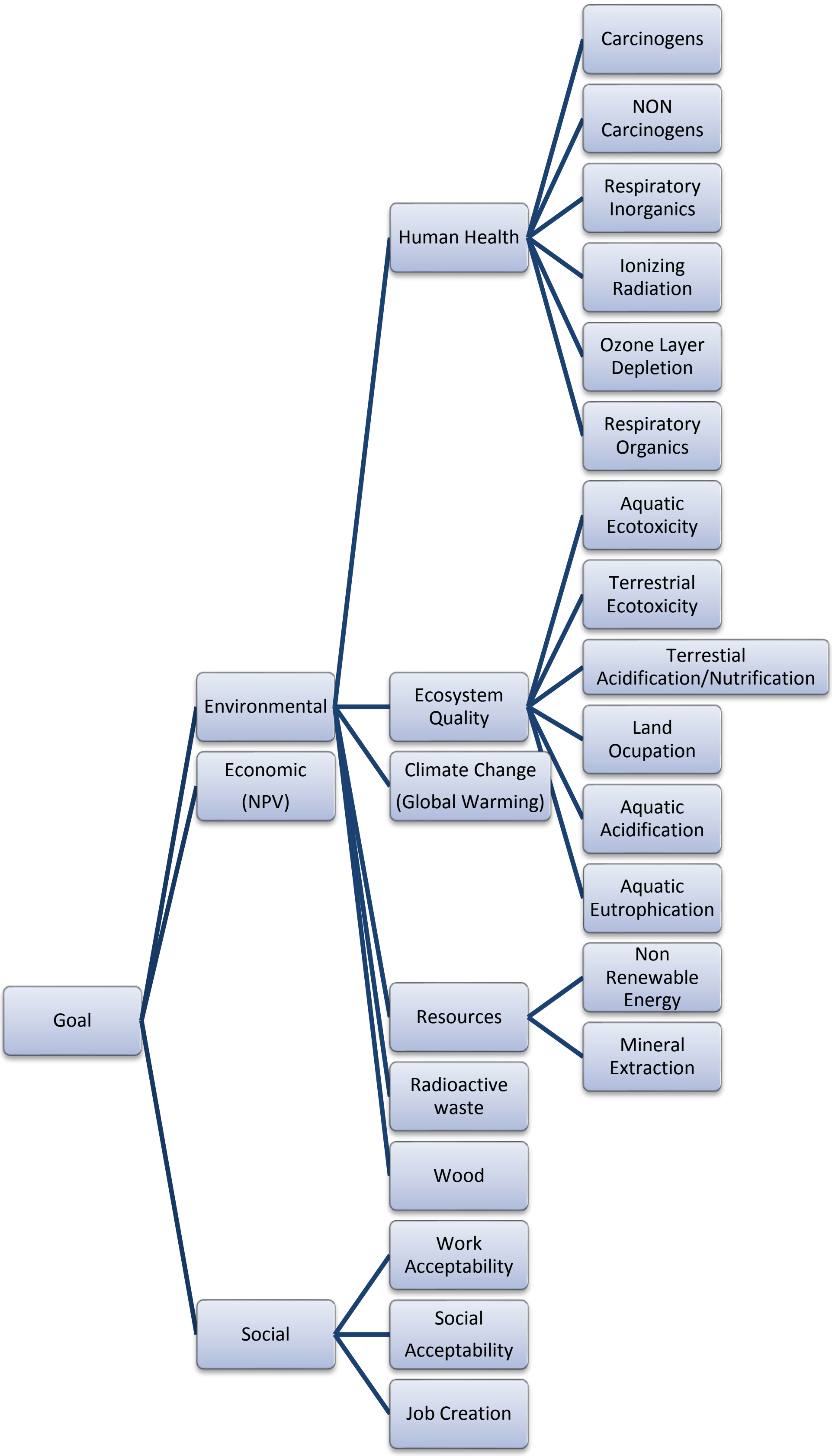

Figure 4. Flow chart of main processes in the integrated plant.

3.3 Application of the model

Three decision-makers with different expertise and outlooks were involved in the project. They are an environmental analyst (d_1), an operator of social care (d_2) and a common citizen (d_3) representing the community. They were asked to assign:

- Weights to the criteria
- Scores to the ten alternatives for qualitative criteria, i.e. social
- Preference/indifference thresholds required by the PROMETHEE method.

Actually, the ten scenarios reported in Table 1 are perceived differently by the decision-makers. For instance, the increase in the percentage of sorted waste collections in scenarios (s5 to s10) is expected to be preferred by the environmental analyst in terms of social acceptability, while it represents a disadvantage in the selfish viewpoint of the common citizen because sorting waste is a time-consuming activity.

The six steps in the new proposed method, described in Section 3, are subsequently performed.

Step 1: Assignment of fuzzy weights to criteria.

Given a score for the goal equal to 100, decision-makers are asked to assign weights to all the criteria in the hierarchy using normalisation constraints, i.e. Eq. (1). Thus, the sum of the weights assigned by each decision-maker d_1 , d_2 , and d_3 to the criteria 'Environmental', 'Economic' and 'Social' at the highest level in the hierarchy is always 100 (Table 2), and so on up to the leaves criteria.

	Goal	*Environmental*	*Economic*	*Social*
w_1	100	90	3	7
w_2	100	75	15	10
w_3	100	63	7	30

Table 2. The weight assignment at the highest level of the hierarchy.

Eqs. (2) and (3) are used to assign the global fuzzy weights to leaves criteria (see Table 3).

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Leaves criteria	lw_j	mw_j	uw_j
Job creation	2.57	5.74	11.00
Social acceptability	2.57	5.74	11.00
Work acceptability	1.87	4.18	8.00
Carc. eff.	6.25	7.42	8.50
Non-carc.	4.69	5.56	6.38
Resp. in.	3.13	3.71	4.25
Ion. radiation	3.13	3.71	4.25
Oz. l. d.	4.06	4.82	5.53
Photo. ox.	3.75	4.45	5.10
Aquatic ecot.	2.17	2.93	3.77
Ter. ecot.	3.26	4.40	5.66
Ter. acid/nutr	2.71	3.67	4.71
Aq. acid.	2.99	4.03	5.19
Aq. eut.	2.44	3.30	4.24
Land occ.	5.43	7.33	9.43
Glob. warm.	4.00	4.67	5.00
Non-ren. energy	3.33	4.63	6.67
Min. extr.	2.67	3.70	5.33
Radioactive waste	2.00	2.33	3.00
Wood	4.00	5.33	7.00
NPV	3.00	8.33	15.00

Table 3. Fuzzy weights for leaves criteria.

Step 2: Fuzzy decision matrix.

The scores assigned to the alternatives for environmental and economic criteria do not change among decision-makers; they are therefore directly fuzzified. Conversely, d_1, d_2 and d_3 express their crisp judgments on the three social criteria, which are subsequently fuzzified by using the same approach as Step 1 (Eq. 4). The fuzzy decision matrix $\widetilde{D} = \left[\tilde{x}_{i,j}\right]_{10\times 21}$ is then compiled by aggregating the values assigned to the ten alternatives for the twenty-one leaves criteria (see Appendix A).

Step 3: Fuzzy indifference and preference thresholds.

As already underlined, one of the strengths of PROMETHEE consists in enabling decision-makers to establish a preference function for each criterion. The linear preference function depends on the indifference and preference thresholds, which are set by the decision-makers. However, in this case study, the decision-makers prefer not to express any subjective thresholds. Thus a common and objective approach for establishing them is adopted. That is, for any specific criterion, the indifference threshold is set to zero, while the preference threshold is fixed at the maximum distance between the best and the worst alternatives for that criterion. Actually these thresholds, i.e. $q_{m,j}$ and $p_{m,j}$ of Eqs. (6) and (7), are the same for all decision-makers when quantitative criteria are considered, and therefore Eqs. (6) and (7) provide fuzzy numbers with equal lower, modal and upper bounds. However, because the decision-makers have given different scores in $\tilde{D} = [\tilde{x}_{i,j}]_{10\times21}$for the same alternative for the qualitative criteria, different $q_{m,j}$ and $p_{m,j}$ arise, and as a consequence $\tilde{q}_j$ and $\tilde{p}_j$. In Table 4, $p_{m,j}$, $q_{m,j}$, along with the fuzzy $\tilde{p}_j$ and $\tilde{q}_j$ are reported. Measurement units can be seen in Appendix A.

	d_1		d_2		d_3							
	$q_{1,j}$	$p_{1,j}$	$q_{2,j}$	$p_{2,j}$	$q_{3,j}$	$p_{3,j}$	$\tilde{q}_j$ (lq_j, mq_j, uq_j)			$\tilde{p}_j$ (lp_j, mp_j, up_j)		
Job creation	0	35.0	0	30.0	0	45.0	0	0	0	30.0	36.7	45.0
Social acceptability	0	70.0	0	75.0	0	45.0	0	0	0	45.0	63.3	75.0
Work acceptability	0	40.0	0	30.0	0	45.0	0	0	0	30.0	38.3	45.0
Carc. eff.	0	-4486.5	0	-4486.5	0	-4486.5	0	0	0	-4486.5	-4486.5	-4486.5
Non-carc.	0	-3085.0	0	-3085.0	0	-3085.0	0	0	0	-3085.0	-3085.0	-3085.0
Resp. in.	0	-1936.8	0	-1936.8	0	-1936.8	0	0	0	-1936.8	-1936.8	-1936.8
Ion. radiation	0	-2853.6	0	-2853.6	0	-2853.6	0	0	0	-2853.6	-2853.6	-2853.6
Oz. l. d.	0	-1746.5	0	-1746.5	0	-1746.5	0	0	0	-1746.5	-1746.5	-1746.5
Photo. ox.	0	-837.9	0	-837.9	0	-837.9	0	0	0	-837.9	-837.9	-837.9
Aquatic ecot.	0	-77261.6	0	-77261.6	0	-77261.6	0	0	0	-77261.6	-77261.6	-77261.6
Ter. ecot.	0	-4851.5	0	-4851.5	0	-4851.5	0	0	0	-4851.5	-4851.5	-4851.5
Ter. acid/nutr	0	-524.3	0	-524.3	0	-524.3	0	0	0	-524.3	-524.3	-524.3
Aq. acid.	0	-101.5	0	-101.5	0	-101.5	0	0	0	-101.5	-101.5	-101.5
Aq. eut.	0	-283.7	0	-283.7	0	-283.7	0	0	0	-283.7	-283.7	-283.7
Land occ.	0	-1544.2	0	-1544.2	0	-1544.2	0	0	0	-1544.2	-1544.2	-1544.2
Glob. warm.	0	-542.5	0	-542.5	0	-542.5	0	0	0	-542.5	-542.5	-542.5
Non-ren. energy	0	-1117.7	0	-1117.7	0	-1117.7	0	0	0	-1117.7	-1117.7	-1117.7
Min. extr.	0	-1196.2	0	-1196.2	0	-1196.2	0	0	0	-1196.2	-1196.2	-1196.2
Radioactive waste	0	-1852.1	0	-1852.1	0	-1852.1	0	0	0	-1852.1	-1852.1	-1852.1
Wood	0	-650.3	0	-650.3	0	-650.3	0	0	0	-650.3	-650.3	-650.3
NPV	0	11.0	0	11.0	0	11.0	0	0	0	11.0	11.0	11.0

Table 4. Indifference and preference thresholds.

Step 4: Fuzzy preference function.

The calculation of the fuzzy preference functions is exemplified through a sample of comparisons between s1, s2, s3 and s4 for the leave criterion 'work acceptability' (see Table 5) by means of Eqs. (8), (9) and (11). All other fuzzy preference functions are then calculated in this way.

NPV	s1			s2			s3			s4		
	$lP_{ii'}$	$mP_{ii'}$	$uP_{ii'}$	$lP_{ii'}$	$mP_{ii'}$	$uP_{ii'}$	$lP_{ii'}$	$mP_{ii'}$	$uP_{ii'}$	$lP_{ii'}$	$mP_{ii'}$	$uP_{ii'}$
s1	0	0	0	0	0	0.3333	0	0	0.1667	0	0	0
s2	0	0.3478	1	0	0	0	0	0.0435	0.8333	0	0	0.3333
s3	0	0.3043	1	0	0	0.6667	0	0	0	0	0	0
s4	0.2222	0.7391	1	0	0.3913	1	0	0.4348	1	0	0	0

Table 5. An example of fuzzy preference functions.

Step 5: Fuzzy flows.

Leaving flows $\tilde{\phi}_i^+$, entering flows $\tilde{\phi}_i^-$ and net flows $\tilde{\phi}_i^{net}$ are respectively calculated by means of Eqs. (11), (12) and (13) for all alternatives (see Table 6).

	$\tilde{\phi}_i^+$			$\tilde{\phi}_i^-$			$\tilde{\phi}_i^{net}$		
	$l\phi_i^+$	$m\phi_i^+$	$u\phi_i^+$	$l\phi_i^-$	$m\phi_i^-$	$u\phi_i^-$	$l\phi_i^{net}$	$m\phi_i^{net}$	$u\phi_i^{net}$
s1	7.8524	12.7348	31.8689	43.8386	59.2047	93.7276	-85.8752	-46.4699	-11.9696
s2	12.1626	21.4610	50.5045	8.7039	11.3398	27.5999	-15.4373	10.1212	41.8006
s3	6.9736	10.8357	29.1663	44.4300	59.7404	93.7926	-86.8190	-48.9047	-15.2637
s4	10.7514	18.5426	42.2643	9.1461	13.1182	27.3544	-16.6029	5.4244	33.1182
s5	14.6099	20.0516	36.0217	2.2478	7.6061	31.9892	-17.3793	12.4455	33.7739
s6	13.8220	18.4141	40.5749	3.3103	8.4517	31.4617	-17.6397	9.9624	37.2646
s7	14.4093	20.5362	40.1609	2.2300	5.8016	25.4884	-11.0792	14.7346	37.9310
s8	13.8222	19.0251	42.1072	3.3263	7.8062	29.6223	-15.8001	11.2189	38.7809
s9	14.5431	21.8716	48.9213	2.2535	4.7015	21.5399	-6.9968	17.1701	46.6678
s10	13.8692	21.2878	47.7713	3.3293	6.9902	26.7854	-12.9161	14.2975	44.4420

Table 6. Fuzzy flows.

Step 6: Defuzzification.

Finally, the ranking of the alternatives is achieved by defuzzifying the net flows (see Table 7). This provides the scenarios ordered from the most to the least preferred.

ϕ_i^{net}		Ranking
s1	-48.10	9
s2	12.16	4
s3	-50.33	10
s4	7.31	8
s5	9.61	7
s6	9.86	6
s7	13.86	3
s8	11.40	5
s9	18.95	1
s10	15.27	2

Table 7. The final ranking of scenarios.

As shown in Table 7, the best alternative (i.e. s9) involves the integrated plant, the maximum percentage of sorted waste collection (60%) and the private company involved in the waste collection. However, the preference degree does not always increase with the percentage of sorted waste collection if the private company is engaged to carry out the collection service; the integrated plant is in fact preferred with the current percentage (s2) instead of 40% (s5). This means that efforts to enforce waste sorting are only justified for a percentage of 60%. In fact, the negative perception of d_3 as regards the social acceptability of a higher sorting percentage (see $lx_{i.j}$ of scenarios s5-s10 in Appendix A) is compensated by the higher environmental and economic performance only achieved by the 60% scenario.

The integrated plant is always better than the traditional incinerator, as a result of the much higher environmental performance. Moreover, the cooperative is always penalised with the exception of the 40% scenarios (s5 and s6) due to the lower employment opportunities offered to the community, as well as the higher NPV. On the contrary, in 40% scenarios the cooperative is preferred; this indicates that the positive impact of a higher social acceptability of the cooperative only overcomes the negative impact of the higher NPV in these scenarios.

4. Conclusions

When the number of decision-makers increases and quantitative criteria are coupled with qualitative criteria, which is often the case in complex decision-making processes, the option of reaching a compromise solution is further exacerbated. Waste treatment is a typical research field in which a multitude of stakeholders are involved in decisions.

Despite life cycle assessments representing a consolidated approach for quantitatively evaluating alternative scenarios, they only cover environmental criteria. To have a complete picture of the issue, social and economic criteria should also be integrated in a comprehensive multi-criteria decision analysis. In particular, in this case study, social criteria were the cause of the greatest divergences between decision-makers.

A new group fuzzy PROMETHEE approach has been introduced to select the best waste treatment solution for a natural park area. A PROMETHEE-based method inherits the advantages of its family. It is able to deal with quantitative and qualitative criteria expressed in different units without the need for normalisation. Moreover, many decision-makers with different viewpoints who are involved in decisions are also integrated. Fuzzy logic has been introduced with a novel functionality, and this represents the most innovative contribution of this paper. In contrast to the standard fuzzy approaches, which tackle the individual vagueness of judgments by means of fuzzy numbers, in this contribution the scores assigned by decision-makers are crisp. A subsequent fuzzification approach is thus adopted on encountering divergences within the group due to different viewpoints on the scores with regard to qualitative criteria and the weights to assign the criteria. In other words, in contrast with the traditional concept of individual uncertainty, the concept of group uncertainty has been represented by means of a new fuzzy approach. As a consequence, the definition of the membership function, which is often a difficult task in standard fuzzy logic, is highly simplified. In fact, the lowest, mean and highest scores assigned by decision-makers naturally lead to the construction of a triangular fuzzy number for each evaluation. The selection of the best waste treatment solution has therefore been driven by a robust approach that is capable of encountering a multitude of divergent viewpoints without resorting to subjective membership functions, which are endogenously achieved in our method. From an operative point of view, this represents a clear time saving, but also greater precision as the membership function and the whole process is fully justifiable and reconstructible. However, as the new group fuzzy PROMETHEE approach is based on PROMETHEE, it not only inherits its advantages but also its limitations. In fact, as with any methods based on pairwise comparisons, there may be a rank reversal with the introduction or deletion of an alternative.

The implementation of this proposal in the real case study has shown that the model can be satisfactorily applied, by perfectly merging simplicity and robustness in a very complex decisional process such as the selection of waste treatment. The decision-makers involved in the project have simply expressed their judgments, without any need for specific methodological skills. This finding has reinforced the belief that this model is suitable to participative democratic projects, where everybody can express their opinion. It is worth remarking that the new method is generic enough to be easily applied in other group decision problems.

The new proposed mapping of a group uncertainty with fuzzy logic opens up the way to several future studies. A natural follow-on subject for research is the combination of the new uncertainty mapping with other group MCDA methods. Another future research project is to understand the points of conflicts and then apply negotiation techniques to resolve them.

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References

Achillas C, Moussiopoulos N, Karagiannidis A, et al (2013) The use of multi-criteria decision analysis to tackle waste management problems: a literature review. Waste Manag Res 31:115–29. doi: 10.1177/0734242X12470203

Boesch ME, Vadenbo C, Saner D, et al (2014) An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland. Waste Manag 34:378–389. doi: 10.1016/j.wasman.2013.10.019

Brans JP, Vincke P (1985) A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making). Manage Sci 31:647–656. doi: 10.1287/mnsc.31.6.647

Chhipi-Shrestha GK, Hewage K, Sadiq R (2015) “Socializing” sustainability: a critical review on current development status of social life cycle impact assessment method. Clean Technol Environ Policy 17:579–596. doi: 10.1007/s10098-014-0841-5

Cole RJ, Sterner E (2000) Reconciling theory and practice of life-cycle costing. Build Res Inf 28:368–375. doi: 10.1080/096132100418519

Di Gianfilippo M, Costa G, Pantini S, et al (2015) LCA of management strategies for RDF incineration and gasification bottom ash based on experimental leaching data. Waste Manag 1–14. doi: 10.1016/j.wasman.2015.05.032

Dorini G, Kapelan Z, Azapagic A (2011) Managing uncertainty in multiple-criteria decision making related to sustainability assessment. Clean Technol Environ Policy 13:133–139. doi: 10.1007/s10098-010-0291-7

El Hanandeh A, El-Zein A (2010) The development and application of multi-criteria decision-making tool with consideration of uncertainty: The selection of a management strategy for the bio-degradable fraction in the municipal solid waste. Bioresour Technol 101:555–561. doi: 10.1016/j.biortech.2009.08.048

Erses Yay a. S (2015) Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. J Clean Prod 94:284–293. doi: 10.1016/j.jclepro.2015.01.089

EUR 23021 EN - Joint Research Centre - Institute for Environment and Sustainability. Environmental Assessment of Municipal Waste Management Scenarios: Part I – Data collection and preliminary environmental assessments for life cycle thinking pilot studies, 2007.

EUR 23021 EN/2 - Joint Research Centre - Institute for Environment and Sustainability. Environmental Assessment of Municipal Waste Management Scenarios: Part II – Detailed Life Cycle Assessments, 2007.

Fiksel J, Bruins R, Gatchett A, et al (2014) The triple value model: A systems approach to sustainable solutions. Clean Technol Environ Policy 16:691–702. doi: 10.1007/s10098-013-0696-1

Gamberini R, Del Buono D, Lolli F, Rimini B (2013a) Municipal solid waste management: Identification and analysis of engineering indexes representing demand and costs generated in virtuous Italian communities. Waste Manag 33:2532–2540. doi: 10.1016/j.wasman.2013.06.003

Gamberini R, Gebennini E, Grassi A, Mora C (2008) An innovative model for WEEE recovery network management in accordance with EU directives. International Journal of Environmental Technology and Management 8:348–368. doi: 10.1504/IJETM.2008.017507

Gamberini R, Gebennini E, Rimini B (2009) An innovative container for WEEE collection and transport: Details and effects following the adoption. Waste Manag 29:2846–2858. doi: 10.1016/j.wasman.2009.07.006

Gamberini R, Rimini B, Nicandri P (2013b) Composting of municipal solid waste: An empirical analysis of existing plants. Transactions of the ASABE 56:1887–1893. doi: 10.13031/trans.56.9819

Hauschild MZ, Dreyer LC, Jørgensen a. (2008) Assessing social impacts in a life cycle perspective-Lessons learned. CIRP Ann - Manuf Technol 57:21–24. doi: 10.1016/j.cirp.2008.03.002

Herva M, Roca E (2013) Review of combined approaches and multi-criteria analysis for corporate environmental evaluation. J Clean Prod 39:355–371. doi: 10.1016/j.jclepro.2012.07.058

Hwang CL, Yoon K (1981) Multiple Attribute Decision Making Methods and Applications: A State-of-the-Art Survey, Springer-Verlag, New York.

Ishizaka A, Nemery P (2011) Selecting the best statistical distribution with PROMETHEE and GAIA. Comput Ind Eng 61:958–969. doi: 10.1016/j.cie.2011.06.008

Ishizaka A, Nguyen NH (2013) Calibrated fuzzy AHP for current bank account selection. Expert Syst Appl 40:3775–3783. doi: 10.1016/j.eswa.2012.12.089

[Post print version] Please cite as: Lolli Francesco, Ishizaka Alessio, Gamberini Rita, Rimini Bianca, Ferrari Anna Maria, Marinelli Simona, Savazza Roberto, 2016, *The waste treatment: an environmental, economic and social analysis with a group fuzzy-PROMETHEE approach*, Clean Technologies and Environmental Policy, advance online publication, DOI: 10.1007/s10098-015-1087-6

Jolliet O, Margni M, Charles R, et al (2003) IMPACT 2002 + : A New Life Cycle Impact Assessment Methodology. Int J Life Cycle Assess 8:324–330. doi: 10.1007/BF02978505

Klöpffer W (2008) Life Cycle Sustainability Assessment of Products (with Comments by Helias A. Udo de Haes, p. 95). Int J Life Cycle Assess 13:89–95. doi: http://dx.doi.org/10.1065/lca2008.02.376

Klöpffer W (2003) Life-Cycle based methods for sustainable product development. Int J Life Cycle Assess 8:157–159. doi: 10.1007/BF02978462

Kumar PR, Jayaram A, Somashekar RK (2009) Assessment of the performance of different compost models to manage urban household organic solid wastes. Clean Technol Environ Policy 11:473–484. doi: 10.1007/s10098-009-0204-9

International Standard ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework; International Organization for Standardization: Geneva, Switzerland, 2006.

Laurent A, Bakas I, Clavreul J, et al (2014a) Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. Waste Manag 34:573–588. doi: 10.1016/j.wasman.2013.10.045

Laurent A, Clavreul J, Bernstad A, et al (2014b) Review of LCA studies of solid waste management systems - Part II: Methodological guidance for a better practice. Waste Manag 34:589–606. doi: 10.1016/j.wasman.2013.12.004

Liu H, You J, Lu C, Chen Y (2015) Evaluating health-care waste treatment technologies using a hybrid multi-criteria decision making model. Renew Sustain Energy Rev 41:932–942. doi: 10.1016/j.rser.2014.08.061

Mardani A, Jusoh A, Zavadskas EK (2015) Fuzzy multiple criteria decision-making techniques and applications – Two decades review from 1994 to 2014. Expert Syst Appl 42:4126–4148. doi: 10.1016/j.eswa.2015.01.003

Margallo M, Aldaco R, Irabien Á (2014) Environmental management of bottom ash from municipal solid waste incineration based on a life cycle assessment approach. Clean Technol Environ Policy 16:1319–1328. doi: 10.1007/s10098-014-0761-4

Margallo M, Taddei MBM, Hernández-Pellón A, et al (2015) Environmental sustainability assessment of the management of municipal solid waste incineration residues: a review of the current situation. Clean Technol Environ Policy. doi: 10.1007/s10098-015-0961-6

Milani M, Montorsi L, Stefani M (2014) An integrated approach to energy recovery from biomass and waste: Anaerobic digestion-gasification-water treatment. Waste Manag Res 32:614–625. doi: 10.1177/0734242X14538307

Morrissey a. J, Browne J (2004) Waste management models and their application to sustainable waste management. Waste Manag 24:297–308. doi: 10.1016/j.wasman.2003.09.005

Norris G (2001) Integrating life cycle cost analysis and LCA. Int J life cycle Assess 6:118–120. doi: 10.1007/BF02977849

Quirós R, Gabarrell X, Villalba G, et al (2014) The application of LCA to alternative methods for treating the organic fiber produced from autoclaving unsorted municipal solid waste: case study of Catalonia. J Clean Prod 1–13. doi: 10.1016/j.jclepro.2014.04.018

Rebitzer G, Hunkeler D (2003) Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations. Discussing a Framework. Int J life cycle Assess 8:253 – 256.

Saaty T (1980) The Analytic Hierarchy Process. McGraw Hill, New York.

Sikdar SK (2007) Sustainability and recycle-reuse in process systems. Clean Technol Environ Policy 9:167–174. doi: 10.1007/s10098-007-0087-6

Soltani A, Hewage K, Reza B, Sadiq R (2015) Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management : A review. Waste Manag 1:318–328. doi: 10.1016/j.wasman.2014.09.010

Swiss Centre for Life Cycle Inventories. Ecoinvent database V2.1. Dübendorf, Switzerland. www.ecoinvent.org. 2009.

Tan RR (2008) Using fuzzy numbers to propagate uncertainty in matrix-based LCI. Int J Life Cycle Assess 13:585–592. doi: 10.1007/s11367-008-0032-x

Tan RR (2005) Application of symmetric fuzzy linear programming in life cycle assessment. Environ Model Softw 20:1343–1346. doi: 10.1016/j.envsoft.2004.11.014

Tan RR, Culaba AB, Aviso KB (2008) A fuzzy linear programming extension of the general matrix-based life cycle model. J Clean Prod 16:1358–1367. doi: 10.1016/j.jclepro.2007.06.020

Tan RR, Culaba AB, Purvis MRI (2004) POLCAGE 1.0--a possibilistic life-cycle assessment model for evaluating alternative transportation fuels. Environ Model Softw 19:907–918. doi: 10.1016/j.envsoft.2003.10.004

Tan RR, Culaba AB, Purvis MRI (2002) Application of possibility theory in the life-cycle inventory assessment of biofuels. Int J Energy Res 26:737–745. doi: 10.1002/er.812

UNEP/SETAC (2013) - The methodological sheets for subcategories in social life cycle assessment (S-LCA): pre-publication version. UNEP/SETAC Life Cycle Initiative, Paris.

UNEP/SETAC (2009) Guidelines for social life cycle assessment of products. UNEP/SETAC Life Cycle Initiative, Druk in de weer.

UNEP/SETAC (2011) Towards a life cycle sustainability assessment: making informed choices on products. UNEP/SETAC Life Cycle Initiative, Paris.

Vázquez-Rowe I, Golkowska K, Lebuf V, et al (2015) Environmental assessment of digestate treatment technologies using LCA methodology. Waste Manag. doi: 10.1016/j.wasman.2015.05.007

Vinodh S (2011) Assessment of sustainability using multi-grade fuzzy approach. Clean Technol Environ Policy 13:509–515. doi: 10.1007/s10098-010-0333-1

Zadeh L a. (1965) Fuzzy sets. Inf Control 8:338–353. doi: 10.1016/S0019-9958(65)90241-X

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Appendix A: The fuzzy decision matrix.

	s1			s2			s3			s4			s5		
	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$
Job creation	50.0	60.7	72.0	75.0	76.7	80.0	40.0	51.7	60.0	45.0	57.3	70.0	40.0	64.3	78.0
Social acceptability	20.0	45.0	65.0	40.0	65.0	80.0	40.0	58.3	75.0	70.0	81.7	95.0	25.0	36.7	45.0
Work acceptability	40.0	50.0	60.0	50.0	63.3	80.0	55.0	61.7	70.0	70.0	78.3	85.0	40.0	48.3	55.0
Car. eff. [kgC2H3Cl eq 10-3]	-283.0	-283.0	-283.0	-3608.1	-3608.1	-3608.1	-283.0	-283.0	-283.0	-3608.1	-3608.1	-3608.1	-4767.9	-4767.9	-4767.9
No-car. [kgC2H3Cl eq 10-2]	3068.5	3068.5	3068.5	-9.3	-9.3	-9.3	3068.5	3068.5	3068.5	-9.3	-9.3	-9.3	-16.4	-16.4	-16.4
Resp. in. [kgPM2.5eq 10-4]	640.3	640.3	640.3	-1139.3	-1139.3	-1139.3	640.3	640.3	640.3	-1139.3	-1139.3	-1139.3	-1295.5	-1295.5	-1295.5
Ion. radiation [BqC-14 eq]	-1697.1	-1697.1	-1697.1	-4221.3	-4221.3	-4221.3	-1697.1	-1697.1	-1697.1	-4221.3	-4221.3	-4221.3	-4550.2	-4550.2	-4550.2
Oz. l. d. [kgCFC-11eq 10-8]	-1836.7	-1836.7	-1836.7	-2872.7	-2872.7	-2872.7	-1836.7	-1836.7	-1836.7	-2872.7	-2872.7	-2872.7	-3582.6	-3582.6	-3582.6
Photo. ox. [kg C2H4 eq 10-4]	503.6	503.6	503.6	-246.9	-246.9	-246.9	503.6	503.6	503.6	-246.9	-246.9	-246.9	-333.9	-333.9	-333.9
Aq. ecot. [kg TEG water]	3882.7	3882.7	3882.7	78932.3	78932.3	78932.3	3882.7	3882.7	3882.7	78932.3	78932.3	78932.3	81144.3	81144.3	81144.3
Ter. ecot. [kg TEG soil]	1633.6	1633.6	1633.6	-3012.4	-3012.4	-3012.4	1633.6	1633.6	1633.6	-3012.4	-3012.4	-3012.4	-3216.8	-3216.8	-3216.8
Ter. ac/nut. [kg SO2 eq 10-2]	273.4	273.4	273.4	-225.9	-225.9	-225.9	273.4	273.4	273.4	-225.9	-225.9	-225.9	-250.8	-250.8	-250.8
Aq. acid. [kg SO2 eq 10-2]	4.9	4.9	4.9	-88.6	-88.6	-88.6	4.9	4.9	4.9	-88.6	-88.6	-88.6	-96.6	-96.6	-96.6
Aq. eut. [kg PO4 P-lim 10-4]	-66.1	-66.1	-66.1	-349.8	-349.8	-349.8	-66.1	-66.1	-66.1	-349.8	-349.8	-349.8	-318.5	-318.5	-318.5
L. occ. [m2org.arable 10-3]	196.8	196.8	196.8	1741.1	1741.1	1741.1	196.8	196.8	196.8	1741.1	1741.1	1741.1	1704.5	1704.5	1704.5
Gl. warm. [kg CO2 eq 10-1]	-1798.9	-1798.9	-1798.9	-1834.0	-1834.0	-1834.0	-1798.9	-1798.9	-1798.9	-1834.0	-1834.0	-1834.0	-2340.7	-2340.7	-2340.7
Non-ren. en. [MJ primary]	1210.1	1210.1	1210.1	92.5	92.5	92.5	1210.1	1210.1	1210.1	92.5	92.5	92.5	94.2	94.2	94.2
Min. extr. [MJ surplus 10-3]	1265.7	1265.7	1265.7	69.5	69.5	69.5	1265.7	1265.7	1265.7	69.5	69.5	69.5	70.7	70.7	70.7
Radioactive waste [Kg 10-6]	-9193.8	-9193.8	-9193.8	-9297.1	-9297.1	-9297.1	-9193.8	-9193.8	-9193.8	-9297.1	-9297.1	-9297.1	-11044.6	-11044.6	-11044.6
Wood [m3 10-6]	4871.3	4871.3	4871.3	4221.0	4221.0	4221.0	4871.3	4871.3	4871.3	4221.0	4221.0	4221.0	4325.8	4325.8	4325.8
NPV	17.5	17.5	17.5	20.0	20.0	20.0	13.0	13.0	13.0	14.0	14.0	14.0	16.0	16.0	16.0

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	s6			s7			s8			s9			s10		
	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$	$lx_{i.j}$	$mx_{i.j}$	$ux_{i.j}$
Job creation	50.0	55.0	60.0	60.0	71.7	80.0	55.0	60.7	65.0	75.0	80.0	85.0	65.0	71.7	85.0
Social acceptability	30.0	56.0	83.0	23.0	42.7	60.0	27.0	59.0	85.0	20.0	48.3	80.0	25.0	66.7	90.0
Work acceptability	55.0	65.0	80.0	50.0	56.7	60.0	58.0	67.7	80.0	50.0	65.0	80.0	56.0	73.7	85.0
Car. eff. [kgC2H3Cl eq 10-3]	-4767.9	-4767.9	-4767.9	-4769.1	-4769.1	-4769.1	-4769.1	-4769.1	-4769.1	-4769.5	-4769.5	-4769.5	-4769.5	-4769.5	-4769.5
No-car. [kgC2H3Cl eq 10-2]	-16.4	-16.4	-16.4	-16.4	-16.4	-16.4	-16.4	-16.4	-16.4	-16.5	-16.5	-16.5	-16.5	-16.5	-16.5
Resp. in. [kgPM2.5eq 10-4]	-1295.5	-1295.5	-1295.5	-1296.2	-1296.2	-1296.2	-1296.2	-1296.2	-1296.2	-1296.5	-1296.5	-1296.5	-1296.5	-1296.5	-1296.5
Ion. radiation [BqC-14 eq]	-4550.2	-4550.2	-4550.2	-4550.7	-4550.7	-4550.7	-4550.7	-4550.7	-4550.7	-4550.6	-4550.6	-4550.6	-4550.6	-4550.6	-4550.6
Oz. l. d. [kgCFC-11eq 10-8]	-3582.6	-3582.6	-3582.6	-3583.1	-3583.1	-3583.1	-3583.1	-3583.1	-3583.1	-3583.2	-3583.2	-3583.2	-3583.2	-3583.2	-3583.2
Photo. ox. [kg C2H4 eq 10-4]	-333.9	-333.9	-333.9	-334.2	-334.2	-334.2	-334.2	-334.2	-334.2	-334.3	-334.3	-334.3	-334.3	-334.3	-334.3
Aq. ecot. [kg TEG water]	81144.3	81144.3	81144.3	81136.0	81136.0	81136.0	81136.0	81136.0	81136.0	81120.6	81120.6	81120.6	81120.6	81120.6	81120.6
Ter. ecot. [kg TEG soil]	-3216.8	-3216.8	-3216.8	-3217.6	-3217.6	-3217.6	-3217.6	-3217.6	-3217.6	-3217.9	-3217.9	-3217.9	-3217.9	-3217.9	-3217.9
Ter. ac/nut. [kg SO2 eq 10-2]	-250.8	-250.8	-250.8	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9	-250.9
Aq. acid. [kg SO2 eq 10-2]	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6	-96.6
Aq. eut. [kg PO4 P-lim 10-4]	-318.5	-318.5	-318.5	-318.4	-318.4	-318.4	-318.4	-318.4	-318.4	-318.9	-318.9	-318.9	-318.9	-318.9	-318.9
L. occ. [m2org.arable 10-3]	1704.5	1704.5	1704.5	1704.4	1704.4	1704.4	1704.4	1704.4	1704.4	1704.1	1704.1	1704.1	1704.1	1704.1	1704.1
Gl. warm. [kg CO2 eq 10-1]	-2340.7	-2340.7	-2340.7	-2341.3	-2341.3	-2341.3	-2341.3	-2341.3	-2341.3	-2341.4	-2341.4	-2341.4	-2341.4	-2341.4	-2341.4
Non-ren. en. [MJ primary]	94.2	94.2	94.2	94.1	94.1	94.1	94.1	94.1	94.1	94.0	94.0	94.0	94.0	94.0	94.0
Min. extr. [MJ surplus 10-3]	70.7	70.7	70.7	70.6	70.6	70.6	70.6	70.6	70.6	70.5	70.5	70.5	70.5	70.5	70.5
Radioactive waste [Kg 10-6]	-11044.6	-11044.6	-11044.6	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9	-11045.9
Wood [m3 10-6]	4325.8	4325.8	4325.8	4324.8	4324.8	4324.8	4324.8	4324.8	4324.8	4323.8	4323.8	4323.8	4323.8	4323.8	4323.8
NPV	10.0	10.0	10.0	15.0	15.0	15.0	9.5	9.5	9.5	14.0	14.0	14.0	9.0	9.0	9.0