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

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TITLE:

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

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Abstract

We develop a modified version of the multi-criteria decision aid, ELECTRE III to account for uncertainty in criteria weightings and threshold values. The new procedure, called ELECTRE-SS, modifies the exploitation phase in ELECTRE III, through a new definition of the pre-order and the introduction of a ranking index (RI). The new approach accommodates cases where incomplete or uncertain preference data are present. The method is applied to a case of selecting a management strategy for the bio-degradable fraction in the municipal solid waste of Sydney. Ten alternatives are compared against 11 criteria. The results show that anaerobic digestion (AD) and composting of paper are more environmentally sound options than recycling and composting. AD is likely to outperform incineration where a market for heating does not exist. Moreover, landfilling can be a sound alternative, when considering overall performance and conditions of uncertainty.

Keywords: ELECTRE-SS, municipal solid waste, stochastic, MCDA, LCA
1. Introduction

Multi-criteria decision analysis (MCDA) is commonly used in environmental and infrastructure projects. The term MCDA refers to various methods developed to help decision makers in reaching a better outcome (Loken, 2007). MCDA methods carry inherent advantages such as: (a) the ability to handle difficult decision structures where multiple and often conflicting criteria influence the decision (b) the capacity to account for complex criteria with non-commensurate units and (c) its role in structuring the process of decision making (Mendoza and Martins, 2006). MCDA methods can be broadly classified into two groups: utility or value-function based methods and outranking methods (Lahdelma et al., 2000).

Making decisions using MCDA such as ELECTRE III method require providing precise data about the decision maker’s (DM) preferences such as threshold values and criteria weights (CW). However, DMs are often unwilling or unable to state their preferences accurately (Lahdelma and Salminen, 2001). Moreover, when more than one DM is involved, different DMs may provide conflicting preferences (Lahdelma et al., 2003). Commonly, sensitivity analyses are carried out to investigate the stability of ranking under such conditions of uncertainty. However, sensitivity analyses can be laborious and do not usually allow more than one source of uncertainty to be considered at one time (Bender and Simonovic, 2000; Hyde et al., 2005).
ELECTRE III (Roy, 1978) is a well established and widely used outranking MCDA. It has been successfully used in various municipal-solid-waste decision-making settings (e.g., Hokkanen and Salminen, 1997a; Rogers and Bruen, 1996; Vego et al., 2008; Karagiannidis and Perkoulidis 2009). The process of applying ELECTRE III method starts with identifying DMs and developing both decision alternatives and the criteria by which they can be judged. Next, criteria weights are assigned to each criterion and performance values of each alternative against each criterion are estimated. Finally, threshold values (indifference, preference and/or veto) are developed before ELECTRE III analysis is conducted and a decision is made.

The assignment of threshold values to account for uncertainties in performance values and DM’s subjectivity is a crucial feature of ELECTRE III. However, these thresholds are highly subjective (Hokkanen and Salminen, 1997a; Rogers and Bruen, 1998a). There is evidence, based on simple sensitivity analyses, that small variations in threshold values can affect the final ranking of alternatives (Hokkanen and Salminen, 1997a; Rogers and Bruen, 1998a; Martin and Legert, 2005). However, no systematic attempt has been made to date to study the effect of uncertainty in threshold values on the final ranking of alternatives.

While threshold values shield the ranking outcome from uncertainty in performance values, they offer no protection against uncertainty in criteria weights (CWs) or lack of preference. CWs in ELECTRE III are viewed as votes for different criteria rather than trade-off ratios as is the case in utility-based methods (Keeny and Raiffa, 1976; Vinck 1992; Rogers and Bruen, 1998b). Relatively
small variations in CWs are known to affect the final ranking of alternatives.

Therefore, a systematic incorporation of uncertainty of CWs is essential (Rogers et al., 2000; Figueria et al., 2005). This is especially important since the process of assigning CWs to different criteria can carry significant uncertainties and, in the words of Hokkanen and Salminen (1997b), “[it] is difficult to judge, how well the weights given correspond to the DMs’ actual opinions”. CWs become yet more difficult to estimate in cases where multiple decision makers with conflicting preferences are involved, making ELECTRE III poorly equipped to handle the decision-making problem without the use of external methods to obtain deterministic weight values (Tervonen et al., 2005). In fact, ELECTRE III like most other MCDA methods is built around a single well-defined decision maker (Bender and Simonovic 2000; Proctor and Qureshi 2005) which makes it difficult to account for conflicting weightings by multiple DMs. Rogers and Bruen (1998b) stress the fact that, due to the non-compensatory nature of ELECTRE III, using average weights does not give a true representation of the stakeholders’ preferences.

Bellehumeur et al. (1997), using Monte Carlo simulations, investigated the sensitivity of potential solutions obtained by ELECTRE III analysis to criteria estimations and weights, and found that the final ranking changed significantly under conditions of uncertainty. Lahdelma and Salminen (2002) developed SMAA-3 as an outranking method based on ELECTRE III-type pseudo-criteria, to handle the uncertainty in CWs. They suggested the use of constrained (restricted between a minimum and a maximum range) uniform probability distribution as a
means of handling uncertainty in the DM’s preferences (Lahdelma and Salminen, 2007). Figueira et al. (2005) used an inverse weight-space analysis, modelled on SMAA to determine ranges of CW in ELECTRE III that yield a given ranking outcome. Neither SMAA methods nor the weight-space analysis generated a direct ranking of alternatives. They provided instead a range of CWs that made a given alternative most favourable. Moreover, they did not address uncertainty in threshold values. Nowak (2004) introduced an MCDA method which used the stochastic dominance approach to determine preference and veto thresholds. The method followed the ELECTRE III distillation procedure but did not deal with the uncertainty in the CWs. Tervonen (2007) introduced an SMAA III method which follows the ELECTRE III approach in handling uncertainty in threshold values and weights. The method applied a Monte Carlo analysis to generate the required parameters and then followed the standard procedure of exploitation described in the standard ELECTRE III to calculate three measurements which describe each alternative’s final ranking: the rank acceptability index, pair-wise winning index, and central weight vector. However, generating the uncertain parameters using standard distributions is computationally heavy in the case of criteria weights, resulting in up to 99.9% weight rejection rate (Tervonen, 2007). Furthermore, although SMAA III yields a good feel for the robustness of the ranking of each alternative, it does not result in a clear and complete ranking of alternatives; instead it describes the space of values of criteria weights and threshold values which results in a certain rank for an alternative. One possible way of avoiding these drawbacks is to a) modify the exploitation procedure in a stochastic ELECTRE III
in such a way that the computational cost is reduced and b) generate an overall stochastic ranking index.

In this paper, we present ELECTRE-SS, a new ELECTRE III technique, based on Monte Carlo simulations, which
- accepts weights and threshold values as stochastic variables
- modifies the exploitation procedure through a new definition of the pre-order to obtain a) a clearer and more rational ranking distribution b) faster stochastic analysis
- generates a ranking index (RI) that makes the comparison between performance and reliability of different alternatives easier.

The new technique is suitable for handling uncertainty resulting from multi-DMs who have equal power in the decision making process but may differ in their evaluations of alternatives, as well as imprecise and/or incomplete data and preferences by DMs.

Modellers and DMs, when running Monte Carlo simulations, are forced to assign arbitrary cut-off levels in order to compare the performance of different alternatives. For example, a DM may reject an alternative if it does not rank in the top 3 alternatives 95% of the times. The new technique relieves the DM from the pressure of assigning these arbitrary cut-offs because it generates the RI which is an indicator of the overall performance of the alternative.

The paper is structured as follows. The ELECTRE III formulation with stochastic parameters is first presented and the outranking procedure described.
The new exploitation procedure is then developed and the new ranking index defined. Next, the proposed method is validated and then used to compare various waste management scenarios using the case of Sydney.

2. Methods

2.1. ELECTRE-SS

2.1.1. Problem formulation

We follow a similar procedure to the ELECTRE III method which comprises two phases: outranking phase and exploitation phase (Roy, 1978). The outranking phase builds an outranking matrix by forming an outranking relation between pairs of alternatives. The outranking matrix is then exploited in the second phase to produce a partial pre-order.

Let

\[ G = \{g_1, \ldots, g_j, \ldots, g_n\} \]  

\[ A = \{a_1, \ldots, a_i, \ldots, a_m\} \]  

\[ W \] is the criteria weight vector. CWs are defined as interval stochastic variable.
Let $a$ and $b$ be two alternatives such that $a, b \in A$. Hence, we can define the following relations:

- $aPb$ where alternative $a$ is strongly preferred to $b$
- $aQb$ where alternative $a$ is weakly preferred to $b$
- $aIb$ where alternative $a$ is indifferent to $b$
- $aSb$ where alternative $a$ outranks alternative $b$ that means “$a$ is at least as good as $b$”

Following ELECTRE III we define three thresholds for each criterion:

- Indifference threshold $q_j$
- Preference threshold $p_j$
- Veto threshold $v_j$
with that:

$$q = \left\{ q \in R^n \mid q_{\min} \leq \hat{q} \leq q_{\max} \right\}$$ \hspace{1cm} (4)$$

$$p = \left\{ p \in R^n \mid p_{\min} \leq \hat{p} \leq p_{\max} \right\}$$ \hspace{1cm} (5)$$

$$v = \left\{ v \in R^n \mid v_{\min} \leq \hat{v} \leq v_{\max} \right\}$$ \hspace{1cm} (6)$$

and $\hat{q}_j < \hat{p}_j < \hat{v}_j$

However, in our approach, these thresholds are defined as stochastic variables and can vary along the scale of the criteria value. For simplicity, we assume that each criterion is to be maximized (Lahdelma and Salminen, 2002; Nowak, 2004). Hence we can define the following outranking relations:

$$a P b^j \iff g_j(a) > g_j(b) + \hat{p}_j$$ \hspace{1cm} (7)$$

$$a Q b^j \iff \hat{q}_j < g_j(a) - g_j(b) \leq \hat{p}_j$$ \hspace{1cm} (8)$$

$$a I b^j \iff \left| g_j(a) - g_j(b) \right| \leq \hat{q}_j$$ \hspace{1cm} (9)$$

Values of $w$, $p$, $q$ and $v$ are defined to accommodate stakeholder evaluations. The entire range of DMs evaluations is used to introduce a common level of confidence. When the number of stakeholders is significantly large a specific probability density function (pdf) can be built to represent the entire spectrum of evaluations. However, when the number of stakeholders is not large
enough to derive a pdf, a truncated normal or uniform distribution may be assumed between lower and higher bounds.

2.1.2. Constructing the Outranking Relation

To construct the outranking relation we follow the procedures given in ELECTRE III which requires the construction of a credibility index $\rho(a, b)$ for the outranking relation $aSb$. The credibility index is defined using both a comprehensive concordance index $C(a, b)$ and a discordance index $d_j(a, b)$ for each criterion $g_j \in G$.

Following the definition in ELECTRE III, we calculate the partial concordance index

$$
\hat{c}_j(a, b) = \begin{cases} 
1, & g_{j(a)} + \hat{q}_j \geq g_{j(b)} \\
0, & g_{j(a)} + \hat{p}_j \leq g_{j(b)}, \quad \text{where } j = 1, \ldots, n \\
\frac{\hat{p}_j + g_{j(a)} - g_{j(b)}}{\hat{p}_j - \hat{q}_j}, & \text{otherwise}
\end{cases}
$$

(10)

The comprehensive concordance index is then calculated as follows:

$$
\hat{C}(a, b) = \frac{1}{K} \sum_{j=1}^{K} \hat{w}_j \times \hat{c}_j(a, b), \quad (11)
$$

where
The discordance index is calculated using a veto threshold ($v_j$). It asserts that within the minority of criteria that do not support the assertion, none is strongly opposed to it (Buchanan and Vanderpooten, 2007).

The degree of credibility of outranking of $b$ by $a$ is defined by the

\[
\rho_j(a, b) = \begin{cases} 
0, & g_j(a) + p_j \geq g_j(b) \\
1, & g_j(a) + v_j \leq g_j(b) \\
g_j(b) - g_j(a) - p_j \quad ^\wedge \\v_j - p_j \quad ^\wedge, & otherwise
\end{cases}
\]  

(13)

Where $J(a, b)$ is the set of criteria such that $d_j(a, b) > C(a, b)$

2.1.3. Exploitation of the Outranking Procedure

To exploit the outranking matrix, two complete pre-orders are constructed; a descending distillation ($Z_1$) and an ascending distillation ($Z_2$) by running the
modified ELECTRE III model multiple times in Monte-Carlo simulation and collecting statistics about the ranks in the $\hat{z}_{1,l}$ and $\hat{z}_{2,l}$ such that:

$$\hat{Z}_1 = \left\{ \hat{z}_{1,1}(a_i), ..., \hat{z}_{1,l}(a_i), ..., \hat{z}_{1,k}(a_i) \right\}$$ (15)

$$\hat{Z}_2 = \left\{ \hat{z}_{2,1}(a_i), ..., \hat{z}_{2,l}(a_i), ..., \hat{z}_{2,k}(a_i) \right\}$$ (16)

$\hat{z}_{1,l}(a_i), \hat{z}_{2,l}(a_i)$ are matrices holding the number of times alternative $a_i$ ranked in the $l^{th}$ order in the descending and ascending distillations respectively.

Second, based on the above distillations, we calculate a penalty scores ($\sigma_1$ and $\sigma_2$) so as to take into account the reliability of each alternative by penalizing poor performance.

$$\sigma_1(a_i) = \sum_{l=1}^{k} -l \times \hat{z}_{1,l}(a_i)$$ (17)

$$\sigma_2(a_i) = \sum_{l=1}^{k} -l \times \hat{z}_{2,l}(a_i)$$ (18)

A total penalty score is then calculated for each alternative as follows:

$$\sigma(a_i) = \sigma_1(a_i) + \sigma_2(a_i)$$ (19)

A final ranking ($Z$) is then constructed by sorting the alternatives in descending order according to their total penalty scores.
This pre-order definition is a departure from previous stochastic ELECTRE III formulations. It carries two significant advantages. It allows a clearer development of rankings and reduces the computational cost of the stochastic analysis because it can be implemented as a simple addition procedure. The modified algorithm deals more rationally with cases where, for example, the cumulative frequency of alternative $a$ is identical to, or higher than, that of $b$ for the $l^{th}$ ranking while, for the $(l-1)^{th}$ ranking, $a$ has a lower cumulative frequency than $b$. Therefore, the stochastic performance of an alternative is based on its overall performance rather than an arbitrary cut-off ranking.

Finally, for easier comparison of the performance of alternatives, a ranking index is calculated as follows:

$$RI_i = \frac{\sigma(a_k)}{\sigma(a_i)}$$  \hspace{1cm} (20)

Where $RI_i$ is the ranking index of alternative $a_i$. RI is defined as the worst alternative’s penalty score ($\sigma_k$) relative to the $i^{th}$ alternative’s cumulative penalty score ($\sigma_i$). Therefore, the alternative with the highest RI is the best performing option.

The RI makes the presentation of results in graphical format clearer and easier to understand because the DM can visually compare the relative performance of each alternative. Moreover, since the RI represents the overall performance, it relieves the DMs from the pressure to agree on a cut-off ranking for comparing the performance of alternatives. Finally, the RI is an attractive tool for communicating
to specific stakeholders, or to the public in general, the reasons behind selecting a particular alternative.

2.2. Validation of ELECTRE-SS

The modified algorithm is applied using visual basic for applications (VBA) with Microsoft Excel®. It is then validated using a case originally published by Karagiannidis and Perkoulidis (2009). The results obtained from ELECTRE-SS are compared to their original findings.

2.2.1. The case

Karagiannidis and Perkoulidis (2009) used ELECTRE III to compare five different technologies for anaerobic digestion of municipal solid waste (MSW); namely: Dranco, Waasa, Valorga, Komogas and BTA. In their analysis they used greenhouse gas emissions (GHGE), recovered energy, recovered material and operating cost as criteria for comparison. The stability and reliability of their results were tested by performing sensitivity analysis on their criteria weights. As a result they found that the ranking of each alternative varied significantly according to the criteria weight assigned. Criteria values used in their analysis are presented in table 1, CWs used are presented in table 2. Karagiannidis and Perkoulidis (2009) concluded that Dranco was best performing alternative followed by Waasa, Valorga was ranked 3rd while Komogas and BTA occupied the 4th and 5th rank, respectively.

(Table 1 here)
2.2.2. Re-analysis using ELECTRE-SS

To verify our model, we re-analysed the case using ELECTRE-SS algorithm in two stages. The first stage aims at duplicating the original results concluded by Karagiannidis and Perkoulidis (2009) without the need to run sensitivity analysis. The second stage aims at demonstrating the effect of errors in estimating threshold values on the final ranking of alternatives.

In the first stage, we established the validity of our model by running ELECTRE-SS with 10000 simulations using the same parameters published by Karagiannidis and Perkoulidis (2009) shown in table 1 and table 2. In this run, we allowed the CWs to be generated stochastically in the range of 0 to 100 while keeping the indifference and preference threshold values at 0. As shown in fig. 1 and fig. 2, ELECTRE-SS reproduces the findings of Karagiannidis and Perkoulidis (2009) under conditions of extreme uncertainty in CWs and strict preference.

In the second stage, we explored the effect of uncertainty in threshold values on the stability of the ranking. We re-analysed the case using the same parameters as in the first run with the exception that the indifference and preference thresholds were generated stochastically in the ranges of [0%, 2%] and [3%, 5%] respectively. As evident from fig. 3 and fig. 4, a small variation in the values of indifference threshold and preference threshold has significant impact on the ranking of alternatives with Waasa outranking Dranco in this case. Hence, the
results highlight the importance of considering uncertainty in threshold values as well as criteria weights.

(Fig. 1. here)

(Fig. 2. here)

(Fig. 3. here)

(Fig. 4. here)

3. Application and results

In this section we demonstrate the usefulness of ELECTRE-SS in the selection of a strategic plan for the treatment of the bio-degradable waste in the MSW of Sydney by combining ELECTRE-SS with life-cycle analysis (LCA) modelling.

3.1. Introduction to Sydney case

Sydney is the largest city in Australia. It has a total population of around 4 million. Sydneysiders produce more than $1.54 \times 10^6$ Mg of MSW each year. More than two thirds of this waste is biodegradable; paper constitutes 26%, food waste is 18% and garden waste is 21%. The waste management system at the moment is heavily dependant on landfilling (85%). However, due to new legislative regulations, the system is under pressure to reduce its dependence on landfills. Therefore, alternatives are being assessed and adopted by the industry.
In this section we assess alternative methods for the management of the biodegradable fraction of MSW in a multi-criteria setting with consideration of uncertainty.

3.2. Management plan alternatives

Ten management alternatives were formulated to treat the organic and paper fractions in the MSW. The plans are formulated to minimize the quantity of waste sent to landfills, increase energy production and decrease GHGE with the exception of S0 which represents the business as usual (BaU) scenario. Table 3 summarises the alternatives in a matrix format for easy reference.

(Table 3 here)

3.3. Selection criteria

Decision making with regard to waste management planning is a complex process which requires considerations of multiple criteria. Among the most important criteria are environmental impacts, economic factors, hazard to humans as well as social, political and regulatory considerations. In this paper we focus on the environmental, health hazard and regulatory concerns. In our analysis we accord equal weights to all criteria groups. Each criteria group is composed of sub-criteria. Table 4 presents criteria used and their weights.

(Table 4 here)
Weights are randomly generated within the ranges presented in table 4 for each criterion by implementing equation 3 using a truncated uniform distribution as follows:

\[ cw_m^r = cw_m^{\text{min}} + (cw_m^{\text{max}} - cw_m^{\text{min}}) \times \text{rand} \] (21)

The generated weights are then normalized using the following equation:

\[ cw_m = \frac{cw_m^r}{\sum_{j=1}^{n} cw_j^r} \] (22)

Weights for the environmental and health hazard criteria are distributed among sub-criteria in proportion to their health and environmental hazard index presented by the National Pollutant Inventory List (NPI, 2007). All sub-criteria in the regulatory group are accorded equal weights within their group.

Indifference and preference thresholds (p and q) are needed for the application of ELECTRE-SS. In addition, a veto threshold may be assigned. However, to avoid the exclusion of any alternative, we do not use the veto threshold. Rogers and Bruen (1998) suggested that indifference value to be set to around 10% and the preference value to be around 20%. Therefore, in our analysis, we assume the indifference value is in the range of 7% - 13% and the preference threshold is in the range of 15% - 25%.

Performance values for all criteria are obtained through LCA modelling. Table 6 summarises the values used in the analysis.

(Table 5 here)
3.4. Results and analysis

The results of our analysis are presented in fig 5. Alternatives which are based on anaerobic digestion are ranked highest. Composting based alternatives performed poorly while incineration based alternatives are ranked in the middle range.

Alternative S9 which is a combination of landfilling of food waste and anaerobic digestion of paper and green waste is ranked first followed by S4 which diverts food and green waste to anaerobic digestion while paper is recycled. Alternative S2 which diverts all three streams to anaerobic digestion is ranked third. The business as usual case (S0) is ranked 5th outperforming all the incineration based alternatives.

The alternative ranked last is S1 (composting of all three streams).

Examining the results show that anaerobic digestion (S2, S4, S8 and S9) generally is a better option than composting (S1, S3 and S6) and incineration, mainly because of the higher rates of electricity generation and the associated credits gained for avoided emissions.

The results also confirm the common rule of waste management hierarchy which stipulates that recycling of paper has higher benefits than anaerobic digestion and composting. This is evident from the ranking of alternatives S4 which ranked 2nd and S2 which ranked 3rd. Similarly, S1 occupied the 10th and S3 came in the 4th place. This is because of the higher credits gained for avoided emissions which result from the recycling.

A close examination of the results shows that S9 shows superior performance in the environmental and health hazard category. It performs poorly
when it comes to diverting waste away from landfill. Nevertheless, it was ranked as the best overall performing option. This is in line with the findings of Dijkgraaf and Vollebergh (2004) who compared the social cost of landfelling and incineration as alternatives for waste management and concluded that landfilling is the option that minimises the social cost, even in densely populated countries such as the Netherlands where high cost of land may suggest otherwise. Furthermore, Rabl et al. (2008) who compared the ‘external costs’ of landfelling and incineration using the latest results of the European commission research project on the externalities of energy (ExternE), found that landfelling may outperform incineration, the final outcome being dependent on the assumptions made regarding the existence of a market for thermal products. These findings clearly suggest that multi-criteria evaluation of alternatives and conditions of uncertainty may well affect decision outcomes significantly.

S4 is the second runner and it too shows excellent performance in the environmental and health hazard criteria as well as reducing the amount of waste sent to landfill. However, S4 performs poorly in the GHGE criterion. Incineration based alternatives (S5, S6 and S7), despite their good performance in the waste diversion from landfill, performed poorly in the environmental and health hazard and acidification criteria compared to other alternatives. In fact, contrary to the commonly held belief that incineration results in the highest recovery rates of energy from waste, our results show that anaerobic digestion may be a better alternative for energy recovery of degradable waste in situations where there is no market for heating, such as Australia. This is supported by the findings of Murphy
and McKeogh (2004) who studied four alternatives for treating municipal solid waste management in Ireland, and concluded that bio-digestion of waste would out-perform incineration due to the lack of market for thermal products.

Finally, our results show the usefulness of using MCDA such as ELECTRE-SS in combination with LCA modelling as a decision aid tool for MSW management planning under conditions of uncertainty. The tool can also be used in other environmental management fields.

(Fig. 5 here)

4. Conclusion

A new multi-criteria decision aid, called ELECTRE-SS, is developed. ELECTRE-SS can help DMs in conducting more rational negotiations around alternatives that rank close to each other especially where rankings are unstable under uncertainty conditions.

The method is used to assess alternatives for treating the degradable fraction in Sydney’s MSW. Our analysis shows that anaerobic digestion and landfilling with energy recovery should be given more attention when considering alternatives for managing bio-degradable MSW. It also shows that incineration may not be the most effective energy-recovery method in climates where market for heating does not exist. It further shows that composting may deliver less environmental benefits than incineration.
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Figure Captions

**Fig. 1.** Frequency of an alternative obtaining a given or better rank under complete lack of criteria weights and strict preference.

**Fig. 2.** Ranking index of alternatives under complete lack of criteria weights and strict preference.

**Fig. 3.** Frequency of an alternative obtaining a given or better rank using indifference threshold range (0% - 2%) and preference threshold range (3% - 5%).

**Fig. 4.** Ranking index of alternatives with indifference threshold range (0% - 2%) and preference threshold range (3% - 5%).

**Fig. 5.** Ranking of waste management alternatives under conditions of uncertainty.
Tables and figures
Table 1
Performance values of each alternative for each criterion adapted from Karagiannidis and Perkoulidis (2009).

<table>
<thead>
<tr>
<th>Alternative</th>
<th>GHGE (kg CO₂-eq/Mg)</th>
<th>Recovered energy (kWh/Mg)</th>
<th>Recovered material (kg/Mg)</th>
<th>Operating cost (EURO/Mg)</th>
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<td></td>
<td>Maximize</td>
<td>Minimize</td>
<td>Maximize</td>
<td>Minimize</td>
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<td>Valorga</td>
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<td>Dranco</td>
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<td>62</td>
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<td>Kompogas</td>
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<td>BTA</td>
<td>212</td>
<td>700</td>
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<td>95</td>
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Table 2
CWs used in the sensitivity analysis by Karagiannidis and Perkoulidis (2009).

<table>
<thead>
<tr>
<th>Criteria Weight</th>
<th>GHGE (%)</th>
<th>Recovered energy (%)</th>
<th>Recovered Material (%)</th>
<th>Operating cost (%)</th>
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### Table 3
Management strategies for treatment of the organic and paper waste streams

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Food waste</th>
<th>Garden waste</th>
<th>Paper waste</th>
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<tbody>
<tr>
<td>S0</td>
<td>LDF</td>
<td>COMP</td>
<td>RE</td>
</tr>
<tr>
<td>S1</td>
<td>COMP</td>
<td>COMP</td>
<td>COMP</td>
</tr>
<tr>
<td>S2</td>
<td>AD</td>
<td>AD</td>
<td>AD</td>
</tr>
<tr>
<td>S3</td>
<td>COMP</td>
<td>COMP</td>
<td>RE</td>
</tr>
<tr>
<td>S4</td>
<td>AD</td>
<td>AD</td>
<td>RE</td>
</tr>
<tr>
<td>S5</td>
<td>IN</td>
<td>IN</td>
<td>IN</td>
</tr>
<tr>
<td>S6</td>
<td>IN</td>
<td>COMP</td>
<td>IN</td>
</tr>
<tr>
<td>S7</td>
<td>IN</td>
<td>IN</td>
<td>RE</td>
</tr>
<tr>
<td>S8</td>
<td>AD</td>
<td>COMP</td>
<td>AD</td>
</tr>
<tr>
<td>S9</td>
<td>LDF</td>
<td>AD</td>
<td>AD</td>
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</tbody>
</table>

AD: anaerobic digestion, COMP: windrow aerobic composting, IN: incineration, LDF: landfilling with energy recovery.
<table>
<thead>
<tr>
<th>Criteria group</th>
<th>Sub-criteria</th>
<th>Weight (%)</th>
<th>Estimated error (%)</th>
<th>Direction of preference</th>
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<tbody>
<tr>
<td>Environmental</td>
<td>Acidification gases</td>
<td>33</td>
<td>±25</td>
<td>Minimize</td>
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<td></td>
<td>Smog precursors</td>
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<tr>
<td>Health hazards</td>
<td>Heavy metals</td>
<td>33</td>
<td>±25</td>
<td>Minimize</td>
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<tr>
<td></td>
<td>Dioxins</td>
<td></td>
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<tr>
<td>Regulatory</td>
<td>GHGE reduction</td>
<td>33</td>
<td>±25</td>
<td>Maximize</td>
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<tr>
<td></td>
<td>Green energy recovery</td>
<td></td>
<td></td>
<td>Maximize</td>
</tr>
<tr>
<td></td>
<td>Landfilled waste</td>
<td></td>
<td></td>
<td>Minimize</td>
</tr>
</tbody>
</table>
**Table 5**
Performance values of each alternative for each criterion

<table>
<thead>
<tr>
<th>Emission (kg/Mg)</th>
<th>S0</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO\textsubscript{x}</td>
<td>-0.26</td>
<td>0.02</td>
<td>-0.14</td>
<td>-0.25</td>
<td>-0.29</td>
<td>1.12</td>
<td>0.66</td>
<td>0.22</td>
<td>-0.13</td>
<td>-0.19</td>
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<tr>
<td>SO\textsubscript{x}</td>
<td>-0.08</td>
<td>0.00</td>
<td>-0.34</td>
<td>-0.05</td>
<td>-0.14</td>
<td>-0.48</td>
<td>-0.30</td>
<td>-0.21</td>
<td>-0.31</td>
<td>-0.47</td>
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<td>VOCs</td>
<td>2.96</td>
<td>0.17</td>
<td>-0.01</td>
<td>3.01</td>
<td>2.91</td>
<td>0.00</td>
<td>0.05</td>
<td>2.92</td>
<td>0.04</td>
<td>-0.01</td>
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<tr>
<td>PM</td>
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<td>0.00</td>
<td>-0.02</td>
<td>-0.15</td>
<td>-0.16</td>
<td>0.22</td>
<td>0.13</td>
<td>-0.06</td>
<td>-0.02</td>
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<tr>
<td>Pb</td>
<td>-4.61E-06</td>
<td>8.22E-08</td>
<td>-1.37E-05</td>
<td>-3.26E-06</td>
<td>-6.98E-06</td>
<td>-9.29E-06</td>
<td>-6.29E-06</td>
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<td>-1.87E-05</td>
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<tr>
<td>Hg</td>
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<td>3.67E-09</td>
<td>-2.64E-06</td>
<td>-9.44E-07</td>
<td>-1.66E-06</td>
<td>1.64E-03</td>
<td>9.71E-04</td>
<td>6.72E-04</td>
<td>-2.43E-06</td>
<td>-3.62E-06</td>
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<tr>
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<td>1.98E-08</td>
<td>-3.88E-06</td>
<td>-1.38E-06</td>
<td>-2.43E-06</td>
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<tr>
<td>TCDD</td>
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<td>1.45E-15</td>
<td>-3.35E-12</td>
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<tr>
<td>GHGE</td>
<td>-209.28</td>
<td>15.81</td>
<td>-9.42</td>
<td>-251.49</td>
<td>-504.19</td>
<td>-122.72</td>
<td>-72.73</td>
<td>-382.14</td>
<td>18.55</td>
<td>-96.32</td>
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<tr>
<td>Electricity Production (kWh/Mg)</td>
<td>-33.77</td>
<td>0.05</td>
<td>-186.61</td>
<td>-26.26</td>
<td>-70.45</td>
<td>-117.69</td>
<td>-73.92</td>
<td>-67.05</td>
<td>-167.38</td>
<td>-201.51</td>
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<tr>
<td>Landfilled waste</td>
<td>511.20</td>
<td>49.10</td>
<td>235.48</td>
<td>211.74</td>
<td>323.34</td>
<td>68.46</td>
<td>62.90</td>
<td>226.35</td>
<td>163.21</td>
<td>461.64</td>
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</table>
Fig. 1. Frequency of an alternative obtaining a given or better rank under complete lack of criteria weights and strict preference.
Fig. 2. Ranking index of alternatives under complete lack of criteria weights and strict preference.
**Fig. 3.** Frequency of an alternative obtaining a given or better rank using indifference threshold range (0% - 2%) and preference threshold range (3% - 5%).
Fig. 4. Ranking index of alternatives with indifference threshold range (0% - 2%) and preference threshold range (3% - 5%).
Fig. 5. Ranking of waste management alternatives under conditions of uncertainty.