A Multi-Criteria Model for Evaluating Waste Treatment Technologies

Ute Schunke
Leichtweiss-Institute for Hydraulic Engineering, Department of Waste Management
Technical University of Braunschweig, Germany
Email u.schunke@tu-bs.de
and
Vicky Mabin
School of Business and Public Management
Victoria University of Wellington, New Zealand
Email vicky.mabin@vuw.ac.nz

Abstract

This paper describes a multi-criteria model developed to evaluate alternative waste treatment technologies for the treatment of municipal solid waste in Germany. The evaluation is based on legal requirements as well as technical, environmental and cost considerations. Two fictitious but typical examples have been used as a trial, evaluating nine of the technologies available in Germany. The results of the evaluation model will be shown. The model is likely to be used by local councils.

1. Background information/ introduction

1.1 Problem Statement

Responsible waste treatment system for municipal solid waste (MSW) is important for mankind and environment. The German market offers a variety of waste treatment technologies, but which treatment technology is the most appropriate for municipalities or districts? In order to answer this question, it is necessary to find a way to evaluate the technologies regarding their financial, technical and environmental aspects.

1.2 History of waste management in Germany

The modern era of waste management did not begin until the mid-1960s. At that time most of the waste was disposed on a multitude of small dumps spread all over Germany. Most of the small dumps were closed in order to establish a controllable network of disposal areas. By 1993 the original number of 50,000 dumps was reduced to 560 landfills. Today most of the landfills are equipped with a sophisticated multi-barrier system which intends to safeguard the environment and the public (at least for a certain period of time). Environmental laws were later introduced to start to prescribe a treatment of MSW prior to disposal on landfills.

2. Treatment technologies available

Three main kinds of treatment are currently applied in Germany: mechanical-biological, thermal and material specific treatment. In this paper only the aerobic treatment types are considered (that means anaerobic fermentation as a biological treatment type and pyrolysis as an anaerobic thermal treatment type are not covered in this paper).

2.1 Mechanical-biological treatment

This consists of two process steps: mechanical treatment prior to biological treatment. Mechanical treatment embraces several technologies, such as breaking, homogenisation and screening. The mechanically prepared waste is then fed into the aerobic biological treatment process. Waste is built up to rotting windrows which are either self aerated or the air is pressed or sucked through the windrows (in order to supply a sufficient oxygen demand for the aerobic degradation processes). The aim is to reduce the volume as much as possible as well as the contamination of the leachate and any gaseous emissions (after-care period of landfills should be as short as possible).

2.2 Thermal treatment

Waste is treated in incineration plants with high technological effort (specifically a combustion chamber and flue gas scrubbing system). Different treatment types are possible depending on the incineration temperature, the amount of oxygen which is supplied during the incineration process, the velocity of cooling down the waste (quenching) and the recovery of energy and other recyclable goods. The most common incineration plants consist of five components: bunker with a crane for storing the waste (sometimes homogenisation and breaking), charging funnel, grate as charging system of the waste into the combustion chamber, flue gas scrubbing system and chimney for ejection of the waste gas. More sophisticated treatment technologies have additional or modified components. The aim is volume reduction, transforming the waste into little amounts of residual material, such as slag or melt, energy and material recovery if possible, reduction of level of contamination of gaseous emissions.

2.3 Material Specific Treatment

This comprises a combination of mechanical-biological and thermal treatment in order to treat different waste fractions in the most appropriate way so that recovery level can be maximised and the amount of residual material can be minimised. Some fractions, such as organic material are treated best in biological treatment, plastics have a high heating value and therefore thermal treatment is most appropriate. The notion is to separate the waste into many fractions in order to achieve the best result.

All kinds of combinations of different treatment technologies are possible. Treatments differ in the technology which is applied, amount and kind of recovery of energy and material, amount and quality of residual material. The aim is to be flexible (in terms of quantity and quality of the waste), ecological- and cost-oriented in treating and disposing the MSW.

3 Overview of previous evaluation models

3.1 Overall aims of evaluation models

All treatment technologies claim to be a reasonable method regarding technical, environmental as well as economic aspects. The decision concerning which treatment technology is the best or most appropriate for certain boundary conditions requires a reliable basis of data and information as well as a good structure for the decision making process. All important aspects should be taken into consideration for the decision. That would mean not only the technology itself but also aspects of the building and closing down phase of the treatment plant, the input material, the output of the treatment process, the recovery process and disposal of the output, etc.

This aim is very difficult to achieve when evaluating and comparing the waste treatment technologies. One should start with one step at a time in the right direction. In Germany, two different means - the UVP and the EPA - have been developed in order to evaluate products, production processes and technical facilities in terms of their environmental effects (one of the three major aspects). In addition some comparisons between waste treatment technologies have been carried out.

The following paragraphs will cover the two means and the comparisons in order to identify their positive and negative aspects, and the insights from this are then incorporated into the following development of an evaluation guideline.

3.2 UVP (Umweltverträglichkeitsprüfung = environmental impact assessment)

The law on environmental compatibility (Umweltverträglichkeitsprüfungsgesetz = UVPG) lays down the rules as to which waste management projects have to pass an UVP [13]. The identification and evaluation of ecological aspects within the UVP are essential for the decision whether a project gets the final approval and is accepted or not. The UVP includes the investigation, description and evaluation of effects of a project upon human beings, animals, plants, soil, water, air, climate and landscape [3]. The aim is to achieve an efficient environmental protection on a consistent level.

The UVP is supposed to evaluate the effects in an objective, transparent, scientific, exact and comprehensive way. The heart of the UVP is the description of the planned projects, the present state of the location where the project is planned and the surrounding environment. The next step is the prognosis of how the environmental situation would be with and without the planned projects. Finally there is the overall evaluation of possible environmental effects.

The scientific evaluation is done with the help of standards which are mostly stated in environmental laws and guidelines. In cases where no standard exists, it is the job of experts to develop a system which allows the evaluation of effects upon the goods to be protected.

So far no standardised method has been developed for the evaluation. Possible methods for carrying out the evaluation are the use-value-analysis or definition of verbal qualitative arguments. The success of UVP is that participants of an approval procedure are forced to focus their minds on environmental issues and that the procedure itself is widely accepted within Germany. A problem of UVP is that due to the lack of standardised methods to carry out the UVP, many notions have been developed so that the content and methodology of an UVP differ significantly between the states of Germany as well as between local authorities within one state. The integrative approach of the UVP is also problematic because it is nearly impossible to assess all dependencies, interactions and consequences of a project upon the environment [12]. The requirement of doing a comprehensive evaluation is in conflict with the aim of carrying out an effective evaluation procedure in an appropriate length of time.

3.3 EPA (environmental profile analysis = Ökobilanz)

The EPA was created to deal with the problem concerning the choice between a variety of packages for drinks, to consider not only cost and marketing aspects but also environmental aspects. The aim is to detect and evaluate the impact upon the environment during the whole life-cycle of the products by identifying the flow of mass and energy. The focus is to detect and collect data which is objective and quantifiable in order to allow a summing up of the data over the whole life-cycle [10].

The EPA helps to take possible damage to the environment into consideration from the beginning of a planned project to the end by comparing the alternatives and illuminating which one might be the most environmental friendly alternative.

An EPA is divided into three main parts: inventory, impact assessment, and evaluation. The impact assessment should filter the data which were collected in the inventory phase in order to give an overview of the impact upon the environment. The data can be assigned to defined aggregation categories, such as greenhouse effect, depletion of ozone, acidification, eutrofication, eco-toxicology, human-toxicology [2]. The categories can each be assigned a different weight. In the evaluation phase the alternatives are scored within each category so that an overall score can be assigned (either in numeric or verbal form).

It is good to aim to quantitatively measure and evaluate the effects of waste treatment technologies upon the environment but the approach to register all effects is as problematic as the approach of UVP. It is not possible to claim that all parameters have been considered and therefore the EPA is always incomplete so that the quantitative data contain an error of an unknown scale [10]. On the other hand there is a gain in clarity and comprehensibility. Qualitative statements should still be possible with the help of EPA.

The EPA is a useful tool which supports the rationality of the decision process to choose waste treatment technologies. The decision process becomes more transparent and hence more comprehensible when applying the EPA scheme.

3.4 Review of comparisons of waste treatment technologies

Four comparisons have previously been published of waste treatment technologies (IFEU [7]; Fichtner [5]; Wollny [15]; Öko-Institut E.V. [9]). It was not possible to detect many similarities between the comparisons, as they have different boundary conditions, differ in the alternatives, time frame, the area of investigation they consider, use different evaluation criteria and different dimensions to evaluate the alternatives against the criteria, some use weights for the criteria, the level of aggregation of the data differs significantly, as does the scope of the sensitivity analyses.

However, having reviewed the four comparisons, it is possible to make a list of positive and negative points which can be used for the development of an evaluation guideline for waste treatment technologies:

1) At the beginning of the study, the aims should be clearly defined and explained
2) The structure of the study should be clearly defined (maybe a flow chart can be used to support the definition)
3) The alternatives to be compared should be described in sufficient detail
4) The evaluation criteria should be defined and applied carefully, including a sensible measurement scale and a good explanation of how they are measured
5) The criteria should be put into a hierarchy
6) Quantifiable data should be used wherever possible to increase the comprehensiveness and the comprehensibility of the study (but the practicability of the study should be considered as well)
7) The same level of detail should be applied for the investigation of all data (avoid going into too much detail when the data are easy to collect and on the other hand look for enough detail when the data are difficult to find)
8) The criteria should be weighted according to their importance (subjective, should be done for certain boundary conditions and not in general)
9) All uncertainties and problems which arise during the study should be mentioned in the report in order to increase the public acceptance and avoid false exactness
10) The final evaluation should include verbal reasoning as the final decision is always subjective and can best be described and interpreted in verbal form
11) The final outcome of the decision depends on the individual circumstances in the district or the municipality
12) A sensitivity analysis should be carried out at the end of the study in order to test the robustness of the outcome
13) The applied methodology should be simple, transparent, generally applicable or modifiable for individual boundary conditions
14) The applied method should allow for an increase in the size and depth of the comparison if necessary

4. The Development of a Comprehensive Evaluation Guideline

4.1 Aim

The development of a new evaluation guideline should be based on the knowledge gathered from the investigation of a set of waste treatment technologies and the overview of existing evaluation models for waste treatment technologies. The aim is to provide a framework which allows the decision maker to evaluate the efficiency of treatment technologies for municipal solid waste in comparison to each other.

In order to enable the decision maker to reach a profound decision, the evaluation guideline should consider three major aspects: monetary, technical and environmental.

1. The **monetary aspect** is included to identify the relation between technical or environmental standards of the treatment technology compared to the costs they cause (ie the trade-off between monetary aspects and advantages in other areas).
2. The **technical aspect** is included in order to evaluate the technical efficiency of the treatment technologies because very different techniques are available for treating MSW.
3. The **environmental aspect** is included due to the aims which are stated in environmental laws and guidelines as well as other aims concerning sustainable development in Germany.

4.2 The Multi-Criteria Decision Analysis Approach (MCDA)

Multi-criteria Decision Analysis (MCDA) (eg see [1], [6], [4]) offers a structured approach to multiple criteria decision problems, such as the above, which leads the decision maker to feel comfortable about making the decision [1]. The central idea is to split the problem into small parts and consider each part separately to avoid cognitive overload due to complexity, so that better insight can be gained. The following paragraphs concentrate on addressing an evaluation problem (alternatives are known or can be easily identified) with the aggregate value function method (in contrast to other methods such as the outranking approach).

Investigation of multiple criteria decision problems consists of three main overlapping parts: the identification of alternatives, the identification of criteria (or attributes) and the process of evaluation and choice [1]. These three main parts can be broken down into 8 process steps which the decision maker has to carry out (1. problem identification, 2. identification of alternative courses of action, 3. identification of the criteria which are relevant to describe and measure the alternatives, 4. scoring of the alternatives against the defined criteria, 5. setting of weights for each criterion in order to reflect how important the criteria are, 6. synthesis of evaluation results and provisional decision, 7. sensitivity analyses, 8. interpretation of results of the sensitivity analyses and reaching final decision) [8].

The simple multi-attribute value function (MAVF) seems to be the most appropriate approach for the evaluation problem of waste treatment technologies (in contrast to multi-attribute utility function and the Analytic Hierarchy Process) [1]; the V•I•S•A software [14] was the particular MAVF software used. This software is easy to use and the model generated is transparent and comprehensible to any decision maker and provides a good structure. It is a flexible tool that enables the user to explore and learn more about the problem. In going through the evaluation process with the help of the V•I•S•A software the decision makers are forced to investigate the problem in greater depth, and the ease of sensitivity analysis encourages them to not simply accept a final result as the final answer. In addition the structure applied by V•I•S•A is similar to the one used in some of the reviewed comparisons.

4.3 Structure of the comprehensive evaluation guideline

The structure follows the model of the V•I•S•A software and thereby adopts a multi-criteria decision analysis approach. The structured approach is meant to fill the gap of standardised and comprehensible methods for evaluating waste treatment technologies. The decision maker has to complete the eight previously mentioned process steps of MCDA. The evaluation guideline offers support especially for the third process step: the identification of the criteria because it provides a value tree with possible criteria and the detailed description and justification of the criteria, what they include and the way they can be measured.

4.4 The evaluation process

In the first process step, the problem identification, the decision maker has to define the individual circumstances and preferences in order to be able to identify the most efficient and appropriate waste treatment technology for a certain district or municipality. In the second process step, the identification of the alternative courses of action, it is possible to narrow down the high number of all existing waste treatment technologies on the German market by applying pre-emptive criteria. At the end the decision maker should have the feeling that the alternatives represent the complete range of waste treatment concepts which are useful and feasible for the individual situation (but the number should not be too high because the collection of information and data is a very time-consuming process).

The aim of the third process step, the identification of criteria, is to define the criteria so that it is possible to measure the performance of the alternatives in relation to the objectives of the decision maker. The value tree (Figure 1) developed for this evaluation guideline has been generated in an iterative process and tries to meet the five requirements of a good tree: completeness, operationality, decomposability, absence of redundancy and minimum size (Keeney & Raiffa, quoted in [6, p 21]). The tree should be adapted to individual objectives and preferences when applied in an evaluation process.

The **overall criterion** is the efficiency of the waste treatment technology and on the next level there are the three main aspects: the monetary, the technical and the environmental aspect which are further broken down into lower level criteria. Note that the term efficiency is meant to describe the overall merit of the treatment technology rather than being a measure for the effectiveness at converting input into outputs.

The **monetary aspect** is shown in the V•I•S•A model as a single sub-criterion: the specific costs [DM/t_{Input}], which allows the decision maker to include the treatment cost of already existing treatment facilities. The specific costs are broken down into fixed and variable costs, in order to test the flexibility of the treatment technology (the higher the share of fixed costs the less flexible the treatment concept is). The different cost components need to be made comparable in terms of the time of occurrence using for example Net Present Value. A spreadsheet can be used to assemble all the costs and calculate NPVs in order to arrive at the Specific Costs for each alternative.

The **technical aspect** is broken down into seven sub-criteria:
the time periods measured in years [a], the throughput measured in tons of treated waste per year [t/a], the mass reduction, the plant availability, the consistency of the output quality, the plant safety, and the public acceptance.

The **environmental aspects** are described by two types of criteria: those that measure the performance during the treatment period and those that measure the performance of the technology after the final disposal of the residual material. Within the treatment period, there are four sub-criteria: the need of resources, the need of space, the residual material and the emissions during the treatment process.

After the disposal of the residual material on a landfill, emissions still occur and make a so-called after-care period necessary which can last several hundred years. Therefore the time period after the disposal is an important aspect to consider, and its sub-criteria are the space requirements (need of volume), the emissions during the disposal period, and the duration of the emissions.

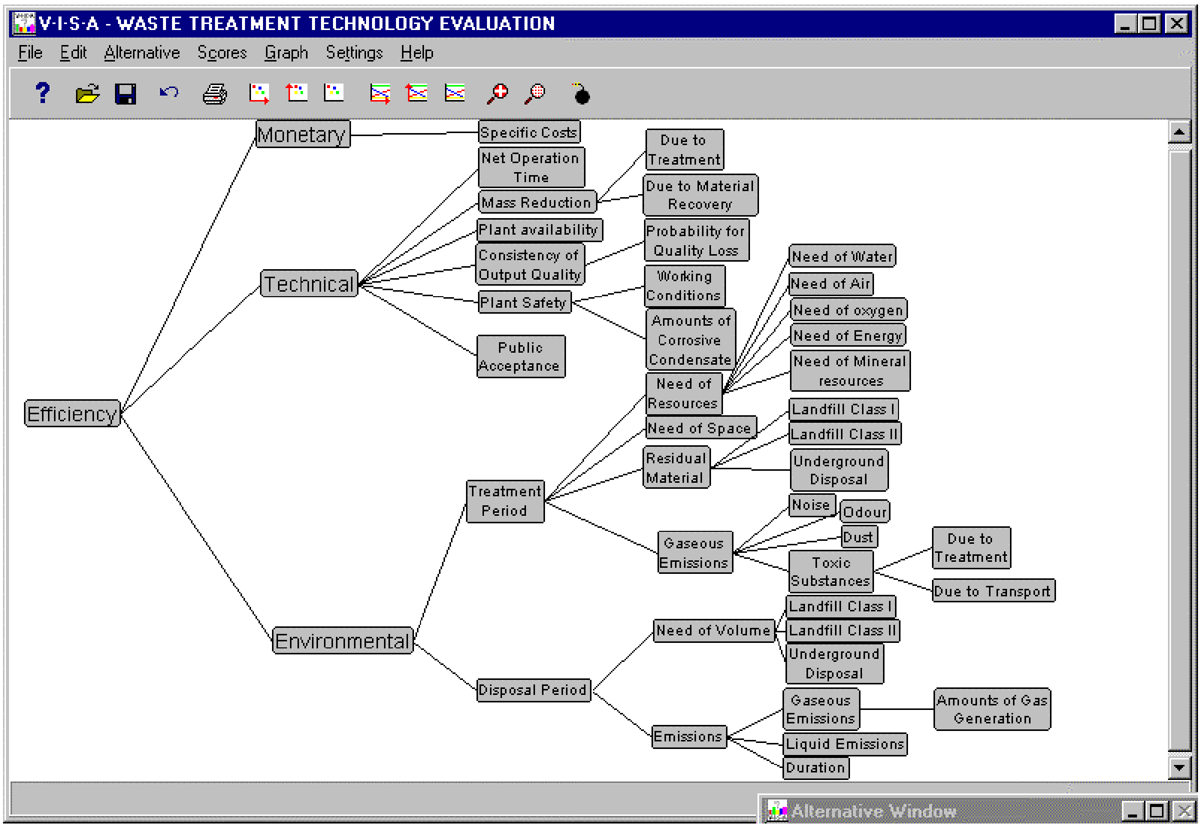

Figure 1: Value tree constructed with V•I•S•A software

Full details of all the criteria are contained in [11]. Risk and uncertainty is not considered in the present value tree as it is assumed that the operation proceeds according to plan but it is possible to additionally include a branch for criteria which capture this notion if desired.

The scoring of the alternatives is the next step in the evaluation process when every alternative has to be scored against each criterion on the lowest level of the value tree. V•I•S•A software supports scoring on an interval scale and this is converted if necessary to a scale from 0 to 100 points. The decision maker has to decide whether to use a local or a global scale dependent on the boundary conditions of the decision problem: if another alternative might be added later then it is better to use global scores, but local scores are easier to use because it is not necessary to score the alternatives with respect to a best and worst possible performance. By assigning weights for each criterion in the fifth process step it is possible to rank the criteria according to their relative importance to the decision maker and their discriminatory power. If a criterion discriminates only little between the alternatives then it might be assigned only a low weight even though it might be of great importance to the decision maker. The decision maker should go through a formal process, such as the swing weights method or the rank order centroid method in order to assign the weights ([6], [1]).

The next step is the synthesis of the initial results. Using the V•I•S•A software, the outcome can be presented in a number of graphs and bar charts. These initial results then have to be tested in the sensitivity analysis to investigate how robust the results are against changes in the data, the weights and scores in particular.

The interpretation of the final results is the last process step and the most important part of the decision-making process because the gained insight and background information as well as the results are used to reach the final decision.

5 Examples

Two examples were generated to test the practicability, meaningfulness and opportunities of the evaluation guideline. These examples have different boundary conditions and represent fairly typical though hypothetical situations. The evaluation guideline is applied in order to determine the most appropriate waste treatment technology for these specific cases; no generally valid statements were anticipated.

5.1 Example 1: Problem description

A rural district with 40,000 t/a municipal solid waste, no sewage sludge, for the next 25 years. The landfill has still enough free space for the next 25 years, incineration plant is 80 km away, underground disposal area is 150 km away and the material recovery station is about 30 km away.

Identification of the alternatives

Eight alternatives are considered (three of each treatment type: mechanical biological, thermal and material specific treatment, except the thermal treatment of option 5 which cannot be realised for so little throughput). For a detailed description of the treatment types see Schunke [11].

Identification of criteria

See the value tree developed for the evaluation guideline

Scoring of the alternatives

The scoring of alternatives is based on literature data and/ or assumptions. Local scores are applied, which means the treatment technology which performs best is assigned a 100 and the worst treatment technology is assigned 0, while the other treatment technologies are scored in relation to these scores. A 100 or a 'high' is always the best score to achieve. For the scores, see Schunke [11].

Weighting of criteria

In the absence of known preferences between the criteria, the discriminatory power of the different criteria was used as the main basis for setting initial weights.

Initial results

The overall winner is option 7 as shown in the thermometer in Figure 2a, but it is not the most stable alternative as it can be seen in the profile in Figure 2b. Options 9 and 2 perform more consistently on the three main criteria.

Sensitivity Analysis

In the sensitivity analysis two basic checks are carried out in order to test the result and gain more insight: changing the weights and changing the scores. It is possible to present the results of the changes in sensitivity graphs (see Schunke [11]).

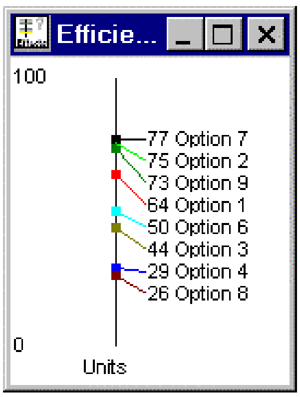

Figure 2a: Thermometer for Example 1

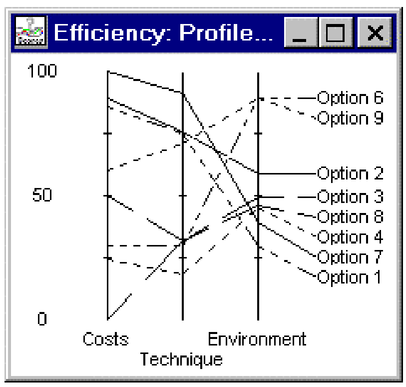

Figure 2b: Profiles chart for Example 1

Interpretation and final decision

The sensitivity analyses have shown that there is a group of top performers which stays more or less the same even for changing weights and scores. It consists of option 7, 2 and 9. Even though option 7 is the top performer with the best overall score, it should be noted that it does not perform very well on the environmental criteria, while option 9 and 2 seem to perform more consistently on the three main criteria.

The final decision cannot be made rationally solely on the basis of the information presented herein but the analysis has been able to identify a group of top performers from which the final choice should be made. All three possibilities are suitable and justifiable for the district and some further investigations with more detail might deliver arguments for the final decision.

5.2 Example 2: Problem description:

In this example, the aim is to choose the most appropriate waste treatment technology for an urban municipality, with 150,000 tons of MSW per year, new treatment facility for the next 25 years, landfill with sufficient free volume for the next 25 years, no existing treatment facilities, underground disposal 150 km away, and material recovery 30 km away.

Identification of alternatives

Nine alternatives (three of each type)

Identification of criteria See value tree of evaluation guideline

Scoring of alternatives

Again the scores are not shown here due to space limitations, but can be found in [11].

Weighting the criteria is done in the exact same way as in example 1

Initial results

The aim is to determine the most appropriate waste treatment technology and to check whether there is a difference in the result compared to example 1. Option 7 is the clear top performer with an even higher score than in example 1. Again the group of top performers comprises options 7, 9, 2 and 1, as is shown in Figure 3.

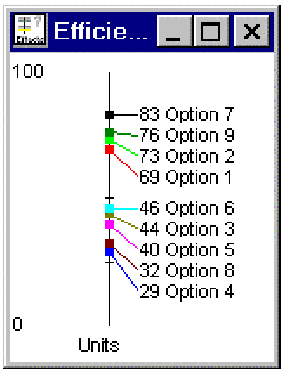

Figure 3a: Thermometer for Example 2

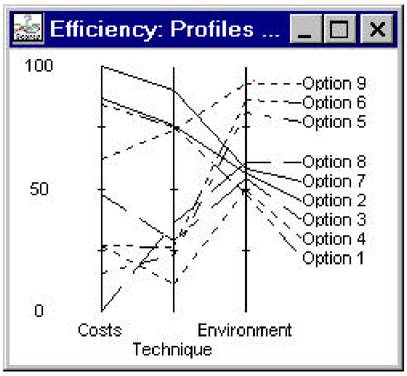

Figure 3b: Profiles chart for Example 2

The profiles of the three main criteria show some differences between the two examples: option 7 scores more consistently over the three criteria and option 9 also performs well on all three criteria (in example 1, it had to share position 1 in the environmental aspects with option 6).

Sensitivity analysis

The sensitivity analysis shows that the group of top performers stays the same but option 1 and 2 do not score that well on some of the sub-criteria and are also very sensitive against changes of the weights on the criteria

Interpretation and final decision

The final decision should be made between option 7 and option 9. Again both options are suitable and justifiable and the decision should be made in the light of further more detailed investigations or subjective preferences.

6 Conclusions

The results of the study show that it is possible to reach a meaningful outcome even though the results of the examples are not scientifically valid due to the lack of information in the literature (data is based on assumptions). The decision maker is able to gain a better insight than with an unstructured approach.

The application of the evaluation guideline revealed the need and opportunities for further investigations and research: the quality of the scoring has to be improved (quantitative scores are the aim), the decision between local and global scales can be further discussed, and the evaluation guideline can be included in a more comprehensive evaluation process.

Overall it can be said that the development of this evaluation guideline is another step in the right direction in order to establish a sensible and responsible waste management concept which still leaves much room for further investigation and research, and refinement based on practical experience from using the guideline.

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