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THE EVALUATION OF WASTE MANAGEMENT OPTIONS

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Until recently the disposal option for municipal waste was selected purely on the grounds of financial effectiveness, but now with an increased concern for the environment other criteria such as resource use and environmental impact must also be taken into consideration. The incorporation of a range of different criteria into the decision making process is, however, a formidable task. One potential solution is to use multicriteria evaluation which provides for a systematic appraisal of a number of alternative projects on the basis of a series of criteria. In this study the multicriteria evaluation of six waste disposal options (landfill, incineration and refuse-derived fuel (RDF), each with and without recycling) resulted in RDF with recycling coming out as the best option under a variety of weighting scenarios. Only when a high weighting was put on cost criterion did landfill become the better option. © 1996 ISWA

Key Words—Waste management, municipal solid waste, incineration, RDF, landfill, recycling, multicriteria evaluation, U.K.

1. Introduction

The evaluation of waste management options can be undertaken in a number of different ways, the most common method being based solely on financial costs and revenues. However, the BATNEEC principle (Best Available Technology Not Entailing Excessive Cost) which now governs the licensing of waste disposal facilities in some countries (e.g. U.K.) implies that other objectives such as environmental effectiveness and economic viability somehow have to be reconciled with financial viability. This paper initially examines the various methods of evaluation that can be used in the assessment and comparison of various waste management options. It then describes and assesses an application of multicriteria evaluation to a range of waste disposal options including landfill, incineration, RDF and recycling.

2. Methods used in the assessment of waste management options

2.1 *Financial assessment*

Waste management options can be assessed in terms of pure financial (i.e. private costs) cost-effectiveness. Disposal options can be evaluated according to their net financial cost per tonne of waste, while recycling schemes can be evaluated according to their financial profitability. Schemes which generate the highest net profitability and/or represent the least costly disposal options would have a high priority in the management strategy (Turner & Powell 1991; Turner 1992). This financial cost criterion approach

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has been dominant in the context of the disposal of waste to landfill in the U.K. The low relative cost of this disposal option, however, reflects only the immediate private costs incurred. In many cases little or no allowance is made for the after-care of the site, and the current and future associated externalities (social and environmental costs).

In general terms the official overall objective of a waste management strategy should be the disposal of waste at the least possible cost to the community with due regard to safeguarding the environment and the use of waste as a resource (Turner & Powell 1991). In the past, little practical notice has been taken of the environmental and economic caveats. However, it should no longer be acceptable to make decisions on solid waste management merely by reference to financial costs and benefits. A range of social and environmental effects must be considered and encompassed within the appraisal process. This can be done by undertaking a full economic evaluation of the waste management options which incorporates the full social (i.e. private plus external) costs and benefits incurred by society as a whole. This is usually carried out via the medium of a social cost–benefit analysis.

2.2 Social cost–benefit analysis

Cost–benefit analysis involves the weighing up of the advantages and disadvantages of an action. A social cost–benefit analysis encompasses both the financial costs and benefits of, for example a waste disposal facility, plus any environmental cost or benefit (Norton 1984). In line with the Polluter Pays Principle, all the social costs of production and consumption must be reflected in the producer's costs of production and in the market price paid by consumers (Turner 1992). However, in reality markets often fail to transfer the full social costs of production and consumption to the producers and consumers. The apparent continuing ability of the environment to absorb our waste products is often treated as virtually a free benefit, and as a consequence there is a risk of over exploitation. In order to protect the environment to socially acceptable standards it will be necessary to regulate the disposal of waste more stringently in the future, thereby substantially increasing the average cost of disposal.

It has been argued that monetary values should be placed on the services provided by the environment. By placing values on these services societies come to learn that natural environments are not free goods, there are limits to what they can provide (Pearce & Turner 1990). There are several different methods for assigning monetary values to environmental benefits or damages (Turner *et al.* 1994). These include: (1) the identification of surrogate markets which act as a proxy for the missing environmental good/service market (i.e. hedonic pricing based on housing market data); (2) market creation, which uses a questionnaire-based social survey to elicit what individuals are willing to pay for an environmental gain or willing to accept as compensation for a loss (i.e. contingent evaluation method); (3) the identification of a dose–response relationship, i.e. a connection between a level of pollution and the damage or loss incurred; and finally, (4) an implicit public preference or value may be identified via legislative and/or regulatory practice. The reasons for the adoption of monetary valuation have been to stimulate awareness, justify a decision, evaluate regulations, so as to indicate relevance to macroeconomic objectives and (rarely) to determine compensation (Pearce & Turner 1990).

It has, however, been argued that either it is not feasible or not necessary to assign monetary values to all environmental costs and benefits in order to determine viable waste policies and/or disposal options; or that a partial cost–benefit analyses (using monetary estimates for a restricted range of impacts) can be supplemented by other non-monetary evaluation methods. The use of "notional" values (whether they are monetised or not) which may turn out on closer inspection to be very imprecise, can initially give an artificial degree of precision only to be followed by practitioner disillusionment. In a comparison of waste disposal options it may be possible to utilise other numeric and physical values such as levels or types of pollution rather than attempting to superimpose "quasi-monetary values" (in the sense of monetary estimates of the underlying values which lack meaning, reliability and validity) on the full range of potential scheme impacts (Bateman & Turner 1993). The following section of this paper explores the potential for, and limitations of, non-monetary evaluation methods and techniques.

2.3 Non-monetary evaluation techniques

Non-monetary evaluation techniques (Janssen 1994) originated in operations research and developed in response to criticism of monetary methods, in particular the use of cost–benefit analysis (Environmental Appraisal Group 1990). Concerns included the drawback that cost–benefit analysis in some situations was only capable of providing partial values for the policy analysis (Nijkamp 1987) and the passive role of the decision maker who is merely led to his decision (Voogd 1983). Since the 1970s a suite of evaluation techniques (forty or more in number) have been developed under the umbrella heading of multicriteria decision analysis. These techniques aim to provide a method for the systematic appraisal of a number of alternative projects, plans, etc. involving a series of criteria which affect groups or individuals in different ways.

Multicriteria techniques, therefore, aim to provide a method for the systematic appraisal of a number of alternatives by a series of criteria which affect groups or individuals in different ways (Voogd 1983; Janssen 1994). Both monetary and non-monetary values can be assessed in addition to non-numerical evaluations. Most of the differences between the various multicriteria evaluation methods arise from the arithmetic procedures used to combine the information from the evaluation matrix (Voogd 1983). In the waste disposal decision-making process multicriteria evaluation can yield some extra insight into the relative importance of financial, resource and environmental considerations (Sobral *et al.* 1981; Maimone 1985).

Most of the studies of waste disposal options which use non-monetary evaluation techniques (Andreottola *et al.* 1989) evaluate the location and the project options together, even though Wilson (1981) considered that a preliminary assessment of the options alone was simpler and more flexible. Maimone (1985) developed a method of planning a solid waste programme in which the first phase involves a full site-independent evaluation of the waste disposal options and subsequent phases which evaluate the site-dependent criteria. Maimone's study (1985) involved a multicriteria technique called Evamix.

3. Methodology

The method used here follows that of Maimone (1985) and evaluates the site-independent criteria for six waste disposal options. A multicriteria model was developed to evaluate incineration, refuse-derived fuel (RDF) and landfill, each with (+) and without (−) recycling. All three waste management options include the recovery of energy which is reclaimed as electricity. Landfill gas is recovered from landfill and RDF is burnt on-site in a dedicated boiler. The gaseous emissions arising from the waste disposal options have been calculated using an integrated solid waste management lifecycle inventory model (White *et al.* 1995). Displaced emissions from both energy and materials recovery are included in the analysis. The electricity generated from waste combustion replaces that generated by fossil fuels, thus saving the associated gaseous emissions. Secondary, recovered materials replace primary materials in the manufacture of new products thus also saving energy and emissions. The impacts arising from the disposal of ash from incineration and RDF combustion are also included, as are the energy and emissions associated with the transport of waste and recovered materials. The recycling data is based on a blue box type separate kerbside collection scheme recovering 25% of household waste (Craighill & Powell 1995).

The cost of the disposal options (ETSU 1992; DoE 1993) include the transport and disposal of residues from landfill and incineration. Other relevant information is summarised in Table 1.

The six waste disposal options were judged against 15 criteria. Cardinal criteria were used where possible but, as Maimone (1985) found, the data were in several instances either unavailable or not considered to be sufficiently accurate. In this particular study the 15 criteria were divided into 10 cardinal and five ordinal criteria (Table 1). Two of the ordinal criteria could be expressed in monetary values and were related to internal and external costs. The remaining 13 criteria were divided into two groups, one encompassing resource use, the other covering environmental impact.

The evaluation matrix (Table 1) is two dimensional with the evaluative criteria forming the rows and the alternatives the columns. Where possible a numerical or cardinal value is used. Where this is not available or if the data are unreliable an ordinal ranking method is employed. For ease of comparison the values are converted so that they conform to the rule "the higher the better". This is done by subtracting the values of each of those criteria which do not conform to this rule (e.g. costs) from the maximum value for that criterion. Full details of the ranking of the options for the various criteria are given in Powell (1991).

3.1 Calculation of the multicriteria evaluation matrix

In a computer program the evaluation matrix with N criteria and P alternatives is first divided into two sub-matrices, one with the C cardinal criteria and the other with the O ordinal criteria. The elements in each matrix are defined by the term e_{ij} where i varies from 1 to C or O, depending on whether the data are cardinal or ordinal, and j varies from 1 to P. A vector is then assigned to each matrix containing the relative weights of the cardinal wc_i or ordinal wo_i criteria, where:

$$\sum_{i=1}^{C} wc_i + \sum_{i=1}^{O} wo_i = 1 \qquad [1]$$

Each alternative e_{ij} is then compared with every other alternative e_{ik} (where $k = 1$ to P) for each criterion to produce a dominance score which represents the degree to which alternative j dominates over alternative k over all criteria. Separate dominance scores

TABLE 1

The evaluation matrix used in the multicriteria evaluation of incineration, RDF and landfill of waste with (+) and without (−) recycling. The 16 criteria are listed in column 1.

	Incin+[a]	Incin−[b]	RDF+[c]	RDF−[d]	Land+[e]	Land−[f]
Cost						
1. Internal cost (£/tonne)	26.25[g]	25.00[g]	26.25	25.00	18.75	15.00
External savings (£/tonne)						
2. −Transport[h]	2.88	2.88	2.88	2.88	0	0
Resources						
3. Land used[j] (ha)	3	3	1	1	13	13
4. % waste eliminated[k]	80	74	98	97	25	0
5. Energy recovered[l] (MJ/tonne)	3611	1754	5416	3294	3360	96
6. % materials recovered[m]	27	4	29	6	25	0
7. Waste categories handled[o]	3	3	1	1	3	3
8. Ease of materials recovery[o]	2	2	3	3	1	1
Environmental impact						
9. Transport[n] (km)	22.28	7.69	22.22	7.63	21.86	6.93
10. % waste incinerated	75	100	17	27	0	0
11. Local air pollution[o] (g/SO_x equiv.)	−3428	−3385	−4692	−5504	−1626	−300
12. Global air pollution (kg CO_2 equiv./t)[o]	−486	390	−1214	−584	−721	156
13. Water/soil pollution[o]	2	2	2	2	1	
14. Relative concs toxic subs[o,p]	1	1	1	1	3	3
15. Disamenity[o]	2	2	3	3	1	1

[a] Incineration with electricity recovery, 25% source separation and ferrous metal recovery at plant.

[b] Incineration as (a) but no source separation.

[c] RDF with 25% source separation and ferrous recovery at plant.

[d] RDF as (c) but no source separation.

[e] Landfill with energy recovery (electricity) and 25% source separation.

[f] Landfill as (e) but no source separation.

[g] Including flue gas cleaning.

[h] Financial savings from reduced transport costs to incineration/RDF plants instead of landfill. Transport costs of residues from incineration/RDF to landfill and recovered materials to reprocessors are included in facility costs.

[j] Data for incineration from Coventry plant (U.K.); RDF data are estimated; landfill data from Department of Environment (1986) & Croft & Campbell (1990).

[k] Includes source separation where applicable, and the reduction of waste by incineration of waste and RDF.

[l] Net energy recovered per tonne waste per year, reduced by in-house energy requirements.

[m] Percentage of total waste stream recovered by source separation and recovery at incineration and RDF.

[n] The distance waste is transported by each disposal option as a substitute for the cost of road congestion.

[o] Ordinal criteria: values expressed as 1–3, the higher the better.

[p] Relative concentration of toxic substances.

for the ordinal A_{jk} and cardinal criteria a_{jk} are calculated. The dominance scores for the ordinal criteria are calculated using the equation:

$$A_{jk} = \sum_{i=1}^{O} wo_i \operatorname{sgn}(e_{ij} - e_{ik}) \qquad [2]$$

$$\text{where } \operatorname{sgn}(e_{ij} - e_{ik}) = +1 \text{ if } e_{ij} > e_{ik}$$
$$= 0 \text{ if } e_{ij} = e_{ik}$$
$$= -1 \text{ if } e_{ij} < e_{ik}$$

For the cardinal data all of the elements e_{ij} in the sub-matrix are first standardised so that the data for each criterion range from 0 to 1 using the equation:

$$E_{ij}=\frac{(e_{ij}-e_i\min)}{(e_i\max - e_i\min)} \quad [3]$$

These standardised scores are then used to calculate the cardinal dominance value a_{jk} using the equation:

$$a_{jk}=\sum_{i=1}^{C} wc_i\,(E_{ij}-E_{ik}) \quad [4]$$

Having calculated the two dominance scores for the ordinal and cardinal data it is then possible to standardise these scores further so that all the ordinal (D_{jk}) and cardinal (d_{jk}) scores lie between 0 and 1. It is then possible to calculate an overall dominance score M_{jk}:

$$M_{jk}=w_oD_{jk}+w_cd_{jk} \quad [5]$$

where w_o and w_c are the sum of all the ordinal and cardinal weights respectively. These overall dominance scores can then be summed to give an appraisal score S_j which represents the worth of alternative j relative to all other alternatives:

$$S_j=\sum_{k=1}^{p} M_{jk} \quad [6]$$

It is these appraisal scores which allow a final ranking of the various waste disposal options.

3.2 *The allocation of weights*

The allocation of a weight to each criterion is required in order to define the priorities of the decision makers (Sobral *et al.* 1981; Maimone 1985). However, the literature on decision theory (Braybrooke & Lindblom 1963; Friend *et al.* 1978, both cited in Environmental Appraisal Group, 1990) reveals that such weights are difficult to realise particularly within the public sector (Environmental Appraisal Group 1990). Often there is no consensus on priorities within a group. Thus a truly representative set of weights is impossible. To overcome this problem, Maimone (1985) created three distinct "points of view" (national, business–economic and environmentalist) in which artificially extreme weights were assigned to particular criteria. For the cardinal data one set of criteria was weighted heavily according to the point of view represented, whilst the remaining weights were distributed lightly over the other criteria. For the ordinal sets priority was given only to the criteria relevant to that point of view, with the other criteria being left out of the evaluation.

In this study the allocation of weights is handled somewhat differently to allow for a more comprehensive sensitivity analysis between the three different viewpoints (financial, resource use and environmental impact). First, the criteria within each group were allocated weights relative to one another such that the weights within each group

TABLE 2
The allocation of weights to individual criteria within each of the three groups of criteria

	Weighting
Cost	
1. Internal cost	1.00
2. Transport cost	
Resource use	
3. Land use	0.20
4. % waste eliminated	0.10
5. Energy recovered	0.25
6. % materials recovered	0.25
7. Waste categories handled	0.15
8. Ease of materials recovery	0.05
Environmental impact	
9. Transport	0.10
10. % waste incinerated	0.10
11. Local air pollution	0.15
12. Global air pollution	0.30
13. Water/soil pollution	0.10
14. Relative concentration toxic substances	0.05
15. Disamenity	0.20

summed to unity (Table 2). The derivation of these weights was a subjective assessment based on the data discussed in Powell (1991).

The sensitivity of the multicriteria evaluation to cost, resource use and environmental impact criteria was explored by varying the weights of each criteria group, with the remaining criteria groups being given equal weight so that the total weight is 1. For example, if the weight on cost criteria is increased to 0.8, the other two criteria groups are each allocated a weight of 0.1. In addition, the multicriteria evaluation was carried out with 100% weight being given to the internal costs.

4. Results

When only the internal costs are taken into account the relative appraisal scores of the six waste disposal options are:

(1) Landfill−	1
(2) Landfill+	0.55
(3) RDF−	0.15
(4) Incineration−	0.15
(5) RDF+	0
(6) Incineration+	0

where 1 is the best score. However, when all the other criteria are included in the analysis and equal weight is given to the three criteria groups; financial cost, resource use and environmental impact, the relative appraisal scores of the six waste options changes considerably:

(1) RDF+	0.58
(2) RDF−	0.52
(3) Landfill+	0.48
(4) Landfill−	0.45
(5) Incineration+	0.43
(6) Incineration−	0.34

where 1 is the best score. Sensitivity analysis has been carried out on the weighting used for the criteria groups. The weighting for each group has been changed while the weighting on the other two criteria groups remains equal.

When the weighting on the financial cost criteria is increased the relative merits of the RDF and incineration options decline, whilst those of landfill increase, particularly landfill without recycling (Fig. 1a). This becomes the best option when the weighting on cost is greater than 42%.

When the percentage weight on environmental criteria increases the relative merits of RDF and incineration options increase against that of landfill which declines (Fig. 1b). RDF with recycling is the best option when the weight on environmental criteria is greater than 10%.

Changes in weight on the resource criteria shows a divergence in the relative score of each option depending on whether recycling is included or not (Fig. 1c). RDF and incineration with recycling increase in merit to a greater extent than the same options without recycling. RDF with recycling is the best option when the weight on resource criteria is greater than 23%. RDF without recycling is the second best option until the weight on resource criteria is greater than 55%, when incineration with recycling becomes the second best option. Landfill with recycling retains the same appraisal score with increased weight on the resource criteria, but landfill without recycling declines in merit.

5. Discussion

In the multicriteria evaluation three results are particularly robust. First, RDF with recycling is the dominant option. Despite considerable variations in the weighting procedure, RDF with recycling obtained the highest appraisal score. It was only when more than 42% of the weighting was given to the financial cost that landfill without recycling gained the highest appraisal score. Second, recycling is advantageous to the waste disposal option apart from when an increased weight is placed on the cost criteria. Although recycling is advantagous from an environmental impact and resource use viewpoint it does impose an additional financial burden. There are also environmental and energy burdens associated with recycling, due to additional transport and energy use arising from the collection, sorting and distribution of the recovered materials. However, this is more than compensated by the energy and emissions savings that can be made by replacing primary materials with recovered secondary materials in the manufacture of new products.

The third robust conclusion is that increased weight on the resource use and environmental impact criteria, rather than on costs increases the attractiveness of RDF and incineration. There are two reasons for this. First, RDF and incineration are considerably more expensive than landfill. Second, RDF and incineration make better use of resources and are consequently less polluting than landfill. All the options that have a high level of energy recovery, either directly or indirectly via recycling, have

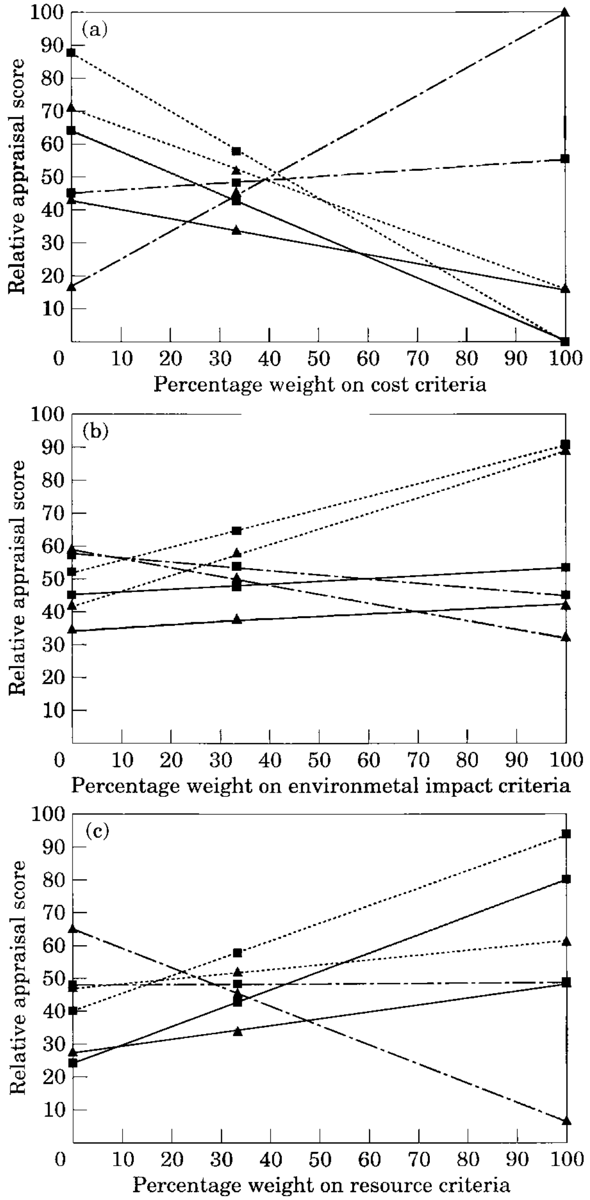

Fig. 1. The relative appraisal of incineration with (incin+) (—■—) and without (incin−) (—▲—) recycling, RDF plants with (RDF+) (– –■– –) and without (RDF−) (– –▲– –) recycling and landfill with (landfill+) (–·–■–·–) and without (landfill−) (–·–▲–·–) recycling as related to the percentage weight put on: (a) cost criteria; (b) environmental impact criteria; and (c) resource criteria in the multicriteria evaluation.

considerable environmental as well as resource advantages. When energy is generated (as in incineration and RDF) or saved, it replaces energy that would have been generated by fossil fuels and to a lesser extent nuclear power. The main fuel used for power generation in the U.K. is coal, which is particularly polluting. The saved emissions from replaced energy are included in this analysis.

These results differ considerably from Maimone (1985) who found that RDF compared poorly with incineration and composting. He found composting to be the best option whilst incineration with recycling was second best from the business–economic and national viewpoint, and landfill with recycling the second best from the environmental point of view. It is not altogether clear why these results are so different from the ones in this study. It may be partly due to the weights used, but Maimone (1985) only provides weights for the national viewpoint in his paper. The private cost estimates he uses are also very different with incineration and RDF being almost six times that of landfill. In comparison the private costs used in this paper are very similar with RDF and incineration only 1.67 times the cost of landfill. The costs that Maimone (1985) uses are average, national figures for the Netherlands which may not be sufficiently accurate. Certainly, using the equivalent U.K. data from the same time period would have provided a very different result in this study as disposal costs have changed significantly in the last 10 years. Also it should be noted that the waste stream on which Maimone's study was based comprised 47% putrescibles, while U.K. domestic waste typically contains 20% putrescibles (Barton, pers. comm. 1992).

While the analysis has shown that RDF is the best option it should be remembered that there are several problems associated with multicriteria evaluation such as the selection of criteria and the need to weight the criteria. The choice of criteria here was a subjective process based on the work of Maimone. Undoubtedly it was not exhaustive and did not, for example, include political or intergenerational equity issues (Sobral *et al.* 1981; Pearce *et al.* 1989). An alternative approach would have been to use the Delphi Technique (Dalkey 1969; Wilson & Jones 1994) where a panel of experts are used to evaluate the weightings and in some cases (Sobral *et al.* 1981) the determination of the set of factors that should be considered (criteria) and the alternatives evaluated. It has been argued, however, that surveys are a time consuming activity and that the most appropriate weighting procedure is to formulate hypothetical alternative qualitative weighting schemes (Voogd 1988).

Some studies have indicated that the sensitivity of certain multicriteria techniques to the allocation of weights is not a particular problem (Giuliano 1985; Cook *et al.* 1989). Buckley (1988), however, argues that methods which depend on the weighting procedure will produce meaningless results. This does not appear to be the case in this study because although the relative weights given to the various criteria have an impact on the relative scores, the best option remains the same even when the weights are radically altered.

6. Conclusions

Despite the problems associated with this method of analysis it clearly provides a flexible structure for the comparison of various options. It is based on principles that are easy to demonstrate, it is relatively cheap, it makes explicit the values and norms upon which the results are to be based, and it is able to illustrate the different outcomes that would occur as a result of modifying the criteria weightings (Voogd 1983; Walshe & Daffern 1990). To some extent multicriteria evaluation can be considered to be a means of structuring a problem rather than finding the solution to the problem (Voogd 1983). The end results from an evaluation can be considered less important than the learning process that is gone through to obtain these results.

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