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Case Study

Nuclear waste management: An application of the multicriteria PROMETHEE methods

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Abstract: Radioactive waste management is an important issue for every electronuclear programme. A particular problem is to know how to finance the waste disposal: indeed, the time span between the electricity production itself and the final disposal in geological formations can represent decades. The problem is made more complex by the choice of a time scenario and of a disposal site. Moreover, the decision-making process involves several points of view of different actors: electricity companies, consumers, public bodies, etc. A multicriteria analysis has therefore been applied, using the PROMETHEE methods and the geometrical representation GAIA. These methods are well adapted to this problem with many actions and few very conflicting criteria.

Keywords: Nuclear waste, multicriteria decision-making, outranking methods

1. Introduction

The disposal of medium and high level radioactive wastes is a complex problem that has very few similarities with other investment problems in today's industrial world. One is faced with a costly investment, the life span of which can vary anything from 70 to 100 years.

The waste considered is that arising from the reprocessing of spent fuel elements discharged from light water reactors, which requires long-term final disposal in geological formation, such as basalt, granite, salt domes, etc. [1].

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The financing method of the long-term investment has to satisfy some principles of equity with regard to future generations and to react as smoothly as possible to unpredicted risks of overcosts. Moreover, various actors are involved: electricity utilities, waste management bodies, present and future public consumers, etc.

This very important aspect of nuclear electricity production has been examined by a Belgian engineering company as part of a study contracted by the Commission of the European Communities [2].

The paper is based on a case study, which might be different in the details from the published results in [2]. This is not essential for the presentation of the main methodological aspects of the approach.

The resulting decision problem has been solved by using a multicriteria analysis. The approach selected is the outranking method PROMETHEE. The decision-making deals with the choice of a financing method adapted to several possible time scenarios for the waste disposal, and to several possible sites selected for the construction of a geological repository [3,4].

2. Description of the decision alternatives

After unloading from the nuclear reactor, the irradiated spent fuel is cooled off for some years; it then undergoes reprocessing, which consists of separating the wastes from the still recoverable fissile materials. The wastes are then conditioned and brought to interim storage.

There are two majors waste categories according to their radioactivity levels: the High and Intermediate Level Wastes (HLW and ILW). The total time span covering all those operations until the final disposal into geological formations represents several decades. Indeed, the interim storage of HLW is very long (at least thirty years). The ILW must be cooled at least 10 years in the interim storage to allow for the decay of the heat producing power.

2.1. The actions of the problem

The scenarios should answer three types of questions about the burial of wastes:
- when? (time scenarios),
- where? (site),
- how? (ways of financing).

The scenarios which have been considered represent the possible actions in the decision problem. To define these actions, we have analysed how to deal with the nuclear waste arising during a thirty year electronuclear programme representing an installed capacity of 25 GWe. It has been assumed that the corresponding waste volume will ultimately fill one large geological repository.

2.1.1. The time scenarios

The three time scenarios given in Table 1 are considered.

Table 1
Three time scenarios for the interim storage of HLW and ILW

	ILW	HLW
S_1	10	30
S_2	30	30
S_3	50	50

In all scenarios studied, it is assumed that the rates of waste production, loading and unloading at the interim storage site, waste transport and its emplacement into repository, are identical.

The typical planning of the waste disposal is illustrated in Figure 1, for the scenario S_2 'ILW 30–HLW 30', as defined in Table 1.

2.1.2. Possible sites

Three possible sites for the geological repository have been considered in the study; we call them R_1, R_2 and R_3. The three sites correspond to different types of geological formations.

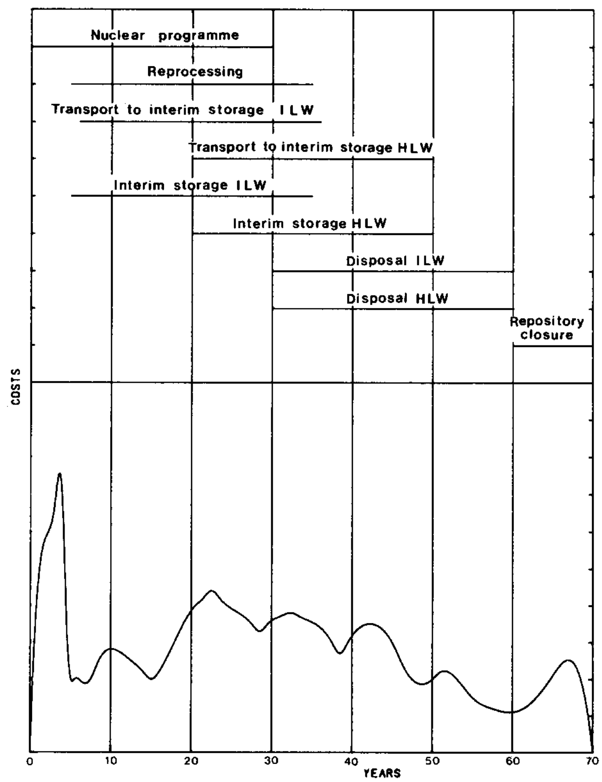

Figure 1. The typical timing diagram for radioactive waste disposal project. Annual distribution of costs is shown in the lower part of the drawing

2.1.3. Ways of financing

The annual cost diagram for a typical disposal scenario is shown in the lower part of Figure 1. The shape of this distribution is very different for each site and time scenario.

The very large time span is, as said before, a decisive feature of the cost diagrams, and makes the financing aspects particularly difficult. Many years separate the production of electricity, responsible for generating the wastes, to the point in time when those wastes are buried. It is therefore very important to know who is going to pay and to respect a principle of justice with regard to future generations.

Three financing methods have been considered in the present study:

The first method (F_1, kWh-fee method) consists of the payment of a fee for each kWh of nuclear electricity produced, i.e. according to our model, during the first thirty years of the time span. Given that the waste is to be stored for a period longer than that over which the electricity will be produced, the fee charged can be paid into a trust fund, which will accumulate interest and thus contribute to covering future expenditure.

The second method (F_2, prorata method) is based on the principle of unlimited responsibility of the waste producer, who has to bear all the costs accruing during waste conditioning, storage and disposal. The payments are due as the costs arise, and they can be made annually or on a multiannual basis.

The third method of financing (F_3, waste-fee method) revolves around fees paid by the waste producer on each unit of waste delivered for geological disposal. All costs incurred before the construction of the repository are financed directly. So are the transportation and interim storage costs. The construction of the repository—before any fees have been paid—is financed by a loan. This loan is repaid thanks to the fee payments during the waste burial period. These payments must also include provisions for the closure of the site, as no more payments are made by then.

2.1.4. The actions

From preceding analysis, it can be seen that the problem involves three possible time scenarios (S_1, S_2, S_3), three sites (R_1, R_2, R_3) and three different methods of financing (F_1, F_2, F_3). Thus, in total, we have a set containing 27 actions, the objective being to rank them according to several evaluation criteria.

2.2. Criterion formation

After careful consideration of the problem, it was decided that the key principles involved are: the total financial cost, 'the polluter pays' concept and the financial risk incurred when adopting a particular method of financing. Four criteria to be described in the following have been modelled according to these principles.

2.2.1. The total financial cost (criterion C_1)

This criterion represents the total of the expenses which are necessary to cover all the technical costs incurred before, during and after dumping of the radioactive wastes (see Figure 1). Note that expenses are not necessarily equal to the costs: for example, in the case of the financing method F_1 (constitution of a trust fund based on a kWh-fee), they are smaller because the fund is interest bearing.

The total financial costs are function of:

(i) the technical parameters related to each geological formation, i.e. R&D costs, site validation, repository construction and exploitation costs;

(ii) the distribution of the costs and the length of the time horizon of the respective scenario, when considering the F_1 and F_3 financing methods.

In calculating the financial cost incurred for each scenario, the following assumptions have been made:

* the rates of inflation (i_f) and nominal interest (i_n) have been taken as 7% and 10% respectively; this means that the real term interest rate (i_r) amounts to about 3%. This is based upon the findings that throughout history the real rate of return on capital invested with financial institutions has been of the order of 2 to 3%.

Hence, cost analysis based on actualization method shows that

(i) the kWh-method of financing (F_1) is in general the most favourable, because of interest earned from the trust fund due to the considerable time lags between the receipts ($t = 0 \rightarrow 30$) and the expenditures, an important percentage of which takes place after $t = 30$;

(ii) the waste-fee method of financing (F_3) is in general the most expensive due to the large interest payments that have to be made on the loan taken and during the site validation stage;

(iii) the prorata-method of financing (F_2) is contrary to F_1 and F_3, independent of the time scale considered, because no interest is generated nor payed.

2.2.2. The 'polluter-pays principle' (criteria C_2 and C_3)

This criterion attempts to measure the social justice of each of the methods of financing considered. Hence, the project time horizon has been split up into two phases. The period $t = 0 \rightarrow 30$ years is identified with *current consumer*—in the model, it corresponds to the electronuclear production generating the wastes to be buried into the repository. The period after $t = 30$ years is identified with the *future consumer*.

C_2 then represents the costs incurred by the present consumers; C_3 are the costs to be supported by the future consumers (although they did not take advantage of the $t = 0 \rightarrow 30$ year electronuclear production).

Note that those two costs do not necessarily sum up to the total financial cost (C_1); their sum may be smaller than, equal to or larger than the latter, according to the method of financing (F_1, F_2, F_3) which includes or not financial charges/products.

2.2.3. Financial risk due to overcosts (C_4)

The real cost of any project is difficult to assess; as said above, the special time dimension of radioactive waste disposal makes the task more difficult indeed.

Risk is therefore related to a wrong assessment: for example, in the case of the kWh-financing (F_1), the risk is to be short of payments after the thirty year fee raising for the fund.

The overcost risks have been assessed using a

Table 2
Relative evaluations of the 3×3×3 actions

	Actions			Normalized criterion evaluation			
	Time scenario	Site	Financing	C_1	C_2	C_3	C_4
1	S_1	R_1	F_1	0.60	0.93	0.00	0.73
2			F_2	0.66	0.55	0.45	0.49
3			F_3	1.00	0.45	0.57	0.50
4		R_2	F_1	0.48	0.87	0.00	0.75
5			F_2	0.62	0.40	0.56	0.50
6			F_3	0.78	0.27	0.71	0.50
7		R_3	F_1	0.40	0.90	0.00	0.82
8			F_2	0.64	0.44	0.54	0.54
9			F_3	0.65	0.30	0.71	0.55
10	S_2	R_1	F_1	0.45	0.86	0.00	0.73
11			F_2	0.61	0.54	0.38	0.49
12			F_3	0.74	0.25	0.80	0.49
13		R_2	F_1	0.48	0.97	0.00	0.91
14			F_2	0.69	0.49	0.56	0.61
15			F_3	0.87	0.03	1.00	0.61
16		R_3	F_1	0.44	0.95	0.00	0.90
17			F_2	0.68	0.40	0.65	0.60
18			F_3	0.76	0.06	1.00	0.60
19	S_3	R_1	F_1	0.35	0.91	0.00	0.98
20			F_2	0.64	0.22	0.81	0.65
21			F_3	0.83	0.25	0.80	0.65
22		R_2	F_1	0.32	0.83	0.00	0.94
23			F_2	0.59	0.24	0.70	0.63
24			F_3	0.73	0.03	1.00	0.63
25		R_3	F_1	0.34	1.00	1.00	1.00
26			F_2	0.71	0.25	0.88	0.67
27			F_3	0.80	0.06	1.00	0.67

probabilistic approach taking into account the amount of possible overcosts, their appearance in time and the ability of each of the financing methods in coping with the overcosts [3].

2.3. Evaluation table

The twenty-seven actions have been evaluated according to the four criteria C_1 to C_4. The Table 2 shows these evaluations as relative values normalized to the maximum ($=1$) observed in each column, for a given criterion [3]. Although some of the actions are dominated, they are taken along in the analysis, as some other criteria not considered here—like some 'political' considerations—may force to disregard some preferred solutions at a later stage of the decision process.

3. Selection of a multicriteria method—PROMETHEE

3.1. Prerequisites

The final aim of the multicriteria analysis is to obtain a complete ordering of the twenty-seven actions defined above, although incomparabilities between actions are not excluded.

An important piece of information is given by the difference in the evaluations of any pair of actions and it should not get lost in the analysis: the larger the difference, the stronger will be the intensity of preference of the one action above the other. The selected method must also be independent on the scales chosen for representing the various criteria.

Moreover, the method has to be easily understood by the Decision-Maker. In any case, 'black box' approaches using technical parameters without any clear economic sense have to be avoided.

3.2. The PROMETHEE methods

We come to the conclusion that the PROMETHEE I and II methods [5] are particularly well suited to meet these requirements. As a further asset, the geometrical representation GAIA accompanying these methods is particularly useful to display the data (cf. [6]).

The PROMETHEE methods are fully described in the literature [5,6] and we give only a brief description of them in this paper.

Let A be a set of n actions and, for each $a \in A$, let $C_j(a)$ be the evaluation of a on criterion C_j ($j = 1, \dots, k$). In a first step of the PROMETHEE methods, a generalized criterion is associated to each of the k criteria. This is obtained by defining a preference function $P_j(a, b)$ that gives for each pair of actions $(a, b) \in A \times A$, the intensity of preference of a over b for criterion C_j. $P_j(a, b)$ varies from 0 to 1: it indicates how the preference of the Decision-Maker increases with the deviation between $C_j(a)$ and $C_j(b)$. The authors of the PROMETHEE methods have proposed six different types of preference functions.

Figure 2 shows the type V preference function that we have used for the four criteria in this study. The $H(a, b)$ function is defined in the following way:

$$H(a, b) = \begin{cases} P(a, b) & \text{if } C(a) \geqslant C(b), \\ P(b, a) & \text{if } C(a) < C(b), \end{cases}$$

for a given criterion C. It displays both the prefer-

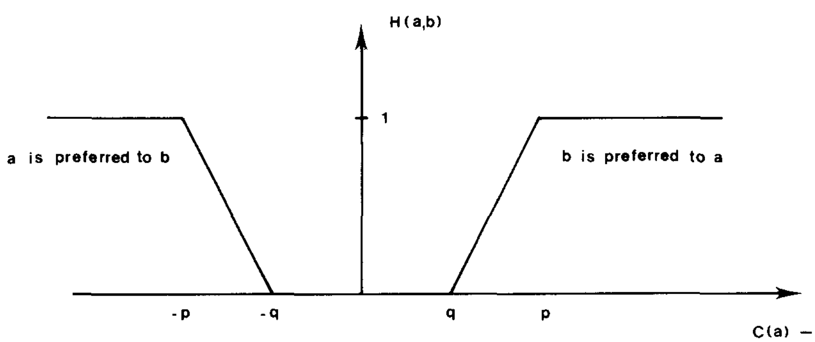

Figure 2. The intensity of preference $H(a, b)$ for the type V function of PROMETHEE. q and p are the indifference and strict preference thresholds respectively

ence of a over b and of b over a. $H(a, b) = 0$ in case of indifference and $H(a, b) = 1$ in case of strict preference. We fixed $q = 0.05$ (indifference threshold) and $p = 0.10$ (preference threshold) for all four criteria.

In a second step, a multicriteria preference index is defined:

$$\pi(a, b) = \sum_{j=1}^{k} w_j P_j(a, b),$$

where w_j ($j = 1, \ldots, k$) are normed weights associated to the criteria, so that $\pi(a, b)$ also varies from 0 to 1, and gives the global intensity of preference of a over b. The following preference flows are then defined:

- *The leaving flow*,

$$\Phi^+(a) = \sum_{b \in A} \pi(a, b).$$

- *The entering flow*,

$$\Phi^-(a) = \sum_{b \in A} \pi(b, a).$$

- *The net flow*,

$$\Phi(a) = \Phi^+(a) - \Phi^-(a).$$

The larger $\Phi^+(a)$ or $\Phi(a)$, the better action a is; the smaller $\Phi^-(a)$, the better action a is. So each flow induces a complete ranking on A.

The PROMETHEE I partial preorder is obtained by considering the intersection of the two rankings induced by Φ^+ and Φ^-. It contains confirmed information and possible incomparabilities between actions.

The PROMETHEE II complete preorder is obtained by considering Φ. It can contain more disputable information as no incomparability is allowed.

The conceptual aspect of the criteria are related to the divergent interests of the various actors (present and future consumers, electricity utilities, public bodies responsible for waste management, etc.) [2]. Because those oppositions cannot be easily eliminated at this stage, equal weights have been assigned to all the four criteria, reflecting our total lack of knowledge about priorities. In a further step, a sensitivity analysis has been performed to test this assumption.

4. Results of the analysis

4.1. The GAIA method

The GAIA method is based on the Principal Components Analysis. Unicriterion net preference flows are considered for the k criteria, one at a time. In this way, the actions are represented by points in a k-dimensional space. The two first principal components (u and v) define a plane on which the actions are projected. The k unit vectors corresponding to the criteria are also projected on this plane. The GAIA plane obtained with our data is given in Figure 3. δ is the percentage of the total inertia that is explained by the plane (u, v). This representation does not depend on the weights of the criteria. The criteria axes point to the direction where the best actions, on each particular criterion, are located, so that it is easy to detect conflicts between criteria. Furthermore, clusters of actions located in a same region of the plane correspond to similar actions.

The study of Figure 3 evidences how actions are grouped according to the corresponding financing technique F_1 to F_3. The actions of the F_1 groups are in the left-hand part of the plane, towards which the criteria C_1 and C_3 are pointing. Those scenarios have vanishing future costs (C_3) and minimum total financial costs (C_1); they are characterized by largest risk values (C_4).

The F_3 family is just opposite in the right-hand side of the plane. For those actions, C_1 is a maximum, while, on the contrary, the present cost (C_2) is at its minimum.

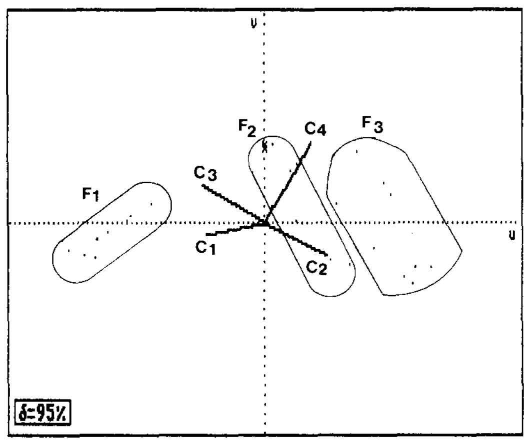

Figure 3. The GAIA plane for the 27 actions and 4 criteria

The actions belonging to the F_2 family are between to the previous one and the origin of the plane. For them, the risk (C_4) is not very high, C_1 and C_2 are moderate and the future costs are relatively quite small.

These actions represent therefore good compromises to resolve the conflicts of the four criteria, which are made obvious by the divergent directions of the arrows representing them.

4.2. *The PROMETHEE I and II methods*

The partial preorder of PROMETHEE I cannot be easily represented in its totality due to the large number of actions. A subgraph is given in Figure 4, showing the seven first actions from the PROMETHEE II ordering.

The total preorder of PROMETHEE II is shown in Figure 5. Figure 4 shows four actions without predecessors: three of them are in the F_2 family (A_{11}, A_5, A_8) and the last one is the F_3 type (A_9). The time scenarios are either S_1 or S_2. The most remote time-scenario S_3 comes later (A_{23}) in the partial preorder graph.

The action leading the total preorder (A_{11})—i.e. the action on top of Figure 5 with the largest value of the net flow—belongs to the F_2 financing family and to the time-scenario S_2. It is an intermediate solution, resolving well the criterion conflicts. The character of good comprise solution attached to A_{11} has been confirmed by the subsequent sensitivity analyses.

A clustering of F_2 type actions is observed at the top and a clustering of F_3 actions at the bottom of the total preorder. This distribution depends of course on the relative weights attached to the criteria.

In Section 4.3.2., we analyse how the ranking is changing in function of the weights.

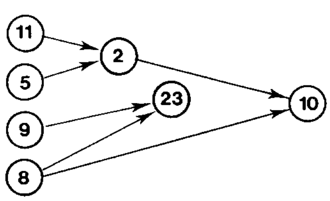

Figure 4. Subgraph showing the PROMETHEE I partial preorder for the reference set of thresholds ($q = 0.05$, $p = 0.10$)

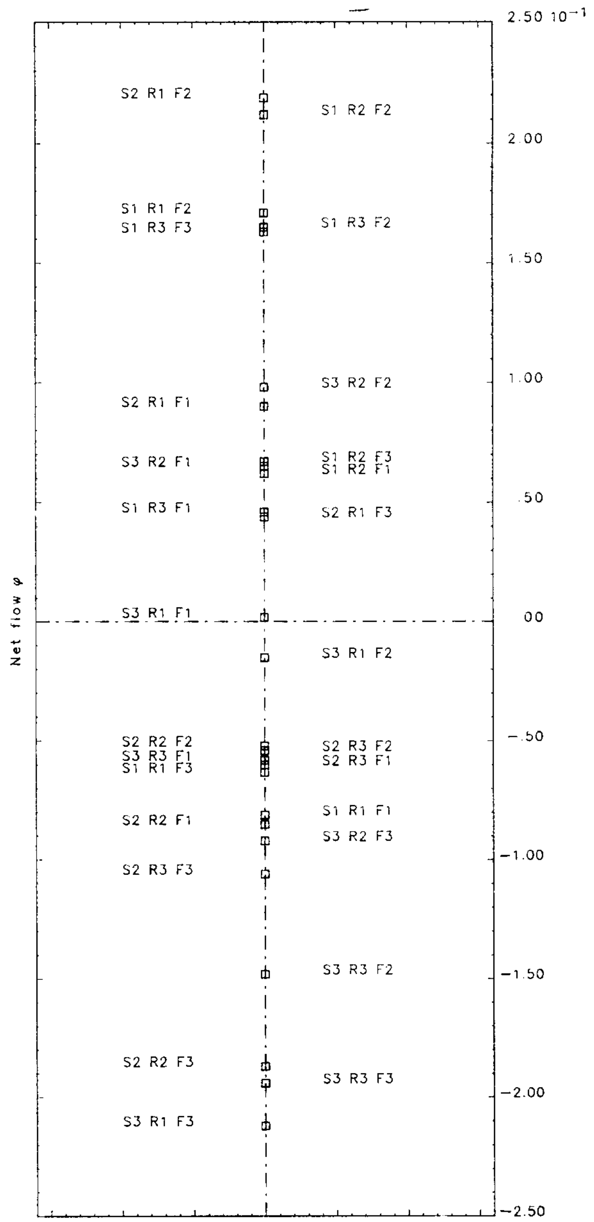

Figure 5. PROMETHEE II total preorder (27 actions) for the reference set of thresholds ($q = 0.05$, $p = 0.10$)

4.3. *Sensitivity analysis*

A sensitivity analysis has been performed on the parameters used as an input to the method: thresholds of the preference functions and criterion weights.

A further study has been dealing on preorders in case of a site selection R_1, R_2 or R_3.

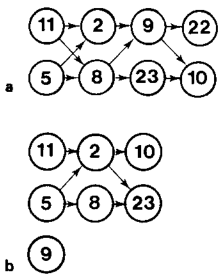

Figure 6. (a) Partial preorder of PROMETHEE I with reduced thresholds ($q = 0.03$, $p = 0.06$). (b) Partial preorder of PROMETHEE I with increased thresholds ($q = 0.07$, $p = 0.14$)

4.3.1. Thresholds

Different sets of thresholds (p, q) have been used rather than ($q = 0.05$, $p = 0.1$) in the reference case:

Set I: $q = 0.03$, $p = 0.06$,
Set II: $q = 0.07$, $p = 0.14$.

The results are shown in Figure 6 for the partial preorders, to be compared with Figure 4, and Figure 7 for the total preorder, to be compared with Figure 5. The overall effect of increasing the indifference and preference thresholds is to reduce the discrimination in the ranking of actions. However, as seen in Figure 7, stability groups are observed (12 first actions; 4 last actions). The maximum sensitivity to the choice of thresholds is observed among the actions with medium ranks.

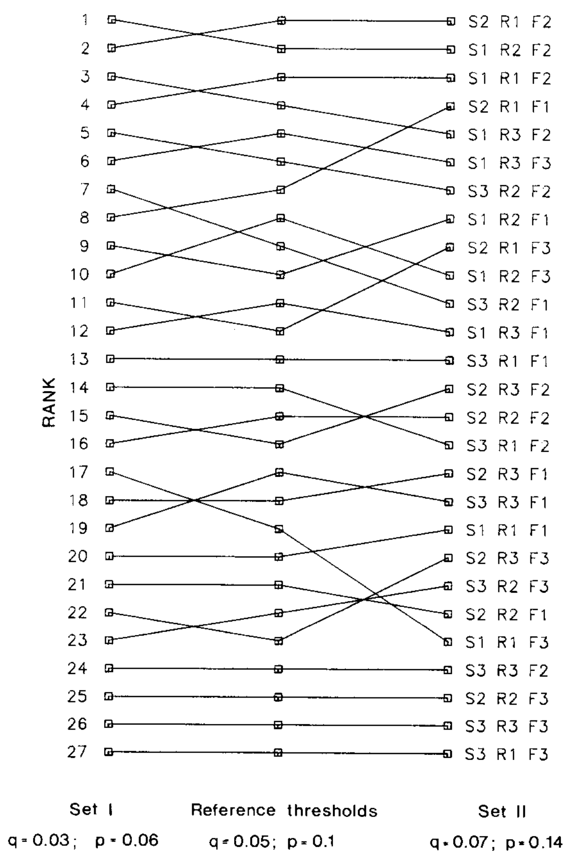

Figure 7. Thresholds sensitivity analysis

Table 3
Weight sensitivity analysis on the PROMETHEE II rankings

Ranks	Reference	Double weight for			
		C_1	C_2	C_3	C_4
1	F_2	F_1	F_3	F_2	F_2
2	F_2	F_1	F_2	F_1	F_2
3	F_2	F_2	F_2	F_1	F_2
4	F_2	F_1	F_3	F_1	F_2
5	F_3	F_2	F_2	F_2	F_3
6	F_2	F_1	F_2	F_2	F_3
7	F_1	F_1	F_3	F_1	F_3
8	F_3	F_2	F_3	F_2	F_3
9	F_1	F_1	F_3	F_1	F_2
10	F_1	F_3	F_2	F_1	F_1
11	F_1	F_2	F_2	F_1	F_2
12	F_3	F_2	F_3	F_1	F_2
13	F_1	F_1	F_3	F_3	F_2
14	F_2	F_1	F_2	F_1	F_1
15	F_2	F_2	F_2	F_2	F_3
16	F_3	F_1	F_1	F_3	F_3
17	F_1	F_3	F_1	F_2	F_1
18	F_1	F_3	F_3	F_3	F_1
19	F_3	F_2	F_1	F_3	F_3
20	F_1	F_2	F_2	F_2	F_2
21	F_1	F_3	F_3	F_2	F_1
22	F_3	F_2	F_1	F_2	F_3
23	F_3	F_3	F_1	F_3	F_3
24	F_2	F_2	F_1	F_3	F_1
25	F_3	F_3	F_1	F_3	F_1
26	F_3	F_3	F_1	F_3	F_1
27	F_3	F_3	F_1	F_3	F_1

4.3.2. Weights

The weight of each criterion has been successively doubled to two, while the other criteria have kept their initial weight equal to one. Table 3 shows how the rankings of financial solutions are modified. As an example, if the weight of C_2 (Present cost) is doubled, the F_1-type solutions loose several ranks, while the F_3-type solutions gain some. If C_4 (risk) gets a larger weight, F_2-type solutions are favoured, while the most risky F_1-type solutions move to the last ranks.

The observed changes are quite important, but remain in a reasonable range, taking into consideration the importance of the variations. It is interesting to note that the largest perturbation occurs whenever the weight of C_2 (present cost) is increased. This stresses the key importance of this criterion in the decision problem.

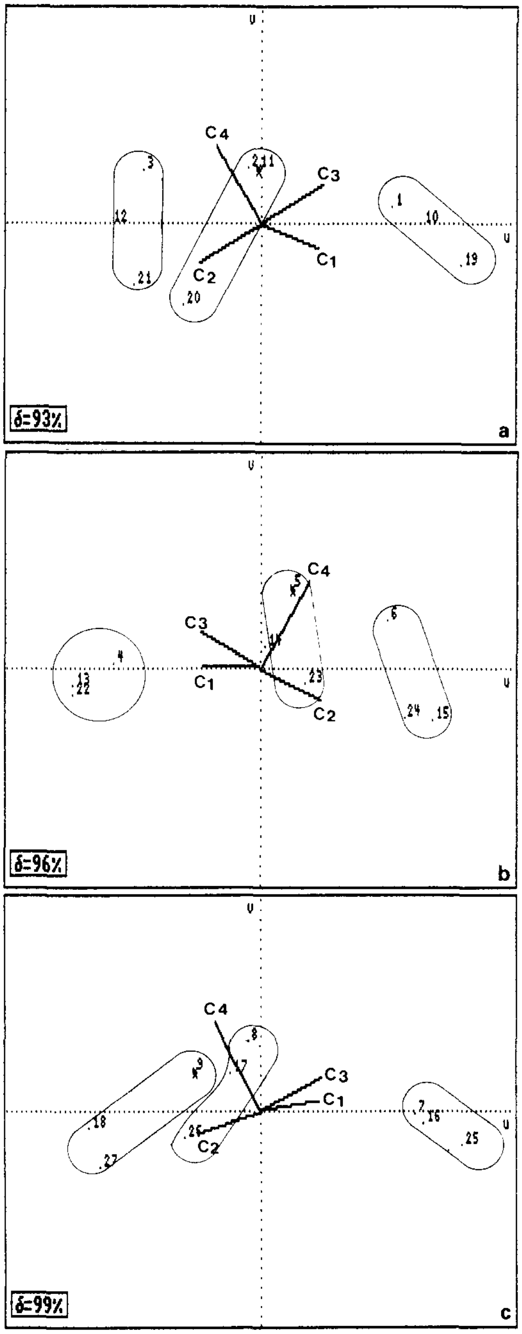

Figure 8. (a) The GAIA plane for the 9 actions corresponding to site R_1. (b) The GAIA plane for the 9 actions corresponding to site R_2. (c) The GAIA plane for the 9 actions corresponding to site R_3

SITES			
R1	R2	R3	RANK
S_2F_2	S_1F_2	S_1F_3	1
S_1F_2	S_1F_1	S_1F_2	2
S_2F_1	S_1F_3	S_1F_1	3
S_2F_3	S_3F_1	S_2F_2	4
S_3F_1	S_3F_2	S_2F_1	5
S_3F_2	S_2F_2	S_3F_1	6
S_1F_3	S_3F_3	S_2F_3	7
S_1F_1	S_2F_1	S_3F_2	8
S_3F_3	S_2F_3	S_3F_3	9

Figure 9. The PROMETHEE II total preorders for each individual site R_1, R_2l, R_3

4.3.3. Imposition of a site

Sometimes, the choice of a site may be imposed on the basis of other criteria or constraints—for instance, of geographical, political or ecological nature, etc.—not taken into account in the present analysis. It might be also decided to build simultaneously more than one repository in different sites.

In such cases, it is necessary to study the decision problem for each individual site. For each of three possible sites considered here, nine solutions are still possible, combining the three financing solutions and the three time scenarios. We have performed those three separate analyses. The representations of the solutions obtained with GAIA are given in Figure 8.

The nine solutions have quite different rankings in each of three sites as shown in Figure 9. The basic explanation for that can be found in the very different time distribution of the costs for the various geological formations (basalt, salt dome, etc.).

5. Conclusion

We have applied the PROMETHEE and GAIA methods to a problem of nuclear waste management. A quite large number of scenarios can be envisaged, which have to be assessed against a small number of strongly conflicting criteria. We have shown how the use of multicriteria method can efficiently assist the search for good solutions, in a descriptive way with GAIA, in a decision-making way with PROMETHEE.

Both methods are in our view well adapted to this type of problems. Moreover, their use is greatly encouraged by the existence of user-friendly softwares, available on PC's [7]. This makes the problem solving easier and faster; it also permits a fast sensitivity analysis as the interface between the Decision-Maker and the decision support system is considerably improved.

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