ELSEVIER

Journal of Hazardous Materials 71 (2000) 321–342

Journal of Hazardous Materials

www.elsevier.nl/locate/jhazmat

Decision support in nuclear emergencies

K.N. Papamichail *, S. French

School of Informatics, Coupland I, University of Manchester, Oxford Road, Manchester M13 9PL, UK

Abstract

In a nuclear emergency, protective actions such as evacuation, sheltering and food bans can be taken to mitigate the consequences of any release of radioactivity. Within the RODOS project, an evaluation framework has been developed to support the assessment of the costs and benefits of potential actions. In order to help the decision makers gain insight into the decision problem and clarify their preferences, guidance can be given in three stages. First, the search of feasible portfolios of protective actions is seen as a constraint satisfaction problem; only those portfolios that satisfy constraints depending on factors such as feasibility are worth further evaluation. Second, the portfolios are ranked based on their consequences and the preferences of the decision makers using either a multi-attribute value or utility function. Third, a natural language report explaining the ranking is produced to help the decision makers gain insight into the decision problem and refine the decision parameters. An intelligent decision system has been developed to demonstrate the feasibility of the framework. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Constraint satisfaction techniques; Explanation; Multi-attribute value function; Risk analysis

1. Introduction

RODOS [1,2] is a Real-time On-line DecisiOn Support system designed to provide off-site emergency management in the event of a radiation accident. Its primary goal is to promote a harmonised and coherent response to any future nuclear emergency in Europe. The RODOS system collects and presents to the decision makers radiological, meteorological, geographic and demographic data. It also analyses and predicts the current and future radiological situation using meteorological, hydrological and other models.

In a nuclear emergency, there are several countermeasures that can potentially mitigate the consequences of the accident: i.e., protective actions that can eliminate or

* Corresponding author. Tel.: +44-161-275-6183; fax: +44-161-275-6286; e-mail: nadia.papamich@man.ac.uk

PII: S0304-3894(99)00086-2

reduce the adverse effects of the accident. The RODOS system simulates early countermeasures such as evacuation and issue of iodine tablets and it calculates their benefits and disadvantages. It also simulates later countermeasures such as food bans, changes in agricultural practice, clean-up actions and resettlement; but we shall not discuss these aspects here.

If a radiation accident occurs, the decision makers will have to take complex decisions. They will have to take into account several factors such as health and psychological effects, public acceptability of their actions and financial costs in the later phases. RODOS will provide them with all the information they need about the radiological situation and the consequences of any potential countermeasures. However, the amount of information the decision makers would have to process could be very large and it is doubtful whether they would be able to take a decision considering all the important factors. In order to help the decision makers make more rational decisions and promote consistency in their decision-making, an evaluation system (ESY) has been developed. The ESY evaluates and ranks alternative strategies. A strategy can be defined as a combination of countermeasures applied to different areas around the nuclear plant.

A significant problem in nuclear emergencies is that there is substantial uncertainty. For example, there are uncertainties on the weather conditions during and after the accident, the source term, the radioactivity measurements, the models used to make predictions and the judgements elicited by the experts. All these uncertainties are reflected in risk estimates and can reduce the value of the results presented to the decision makers. Communicating risks in a nuclear emergency is therefore an issue of paramount importance. However, in a number of elicitation exercises [3] organised to identify the needs of the decision makers during a nuclear emergency, it was obvious that the decision makers found it very difficult to react in a sophisticated way to any uncertainty. Rather they assumed that the worst would happen, replacing uncertainty with certainty.

The ESY supports decision-making throughout all the phases of a nuclear emergency. There are different requirements at each phase. During the early phase (hours or days after the accident), the decision makers are under pressure to take a decision in a short period of time. At the medium phases (days or months after the accident), the decision makers have more time to balance the costs and benefits of the protective actions.

The ESY provides decision support not only in the evaluation of the strategies but also in the formulation and appraisal of the decision problem. An overview of the ESY is given in Section 2. Section 3 discusses how the ESY generates feasible strategies worthy of further evaluation. The evaluation process is described in Section 4. Section 5 presents some results. The ESY is compared against other evaluation systems in Section 6. Conclusions are given in Section 7.

2. An evaluation system for nuclear emergencies

In RODOS there are three types of modules:

- Analysing subsystem modules (ASY) that process incoming data and predict the radiological situation at the present and in the future.

- Countermeasure subsystem modules (CSY) that simulate countermeasures such as evacuation, sheltering and food ban and calculate their costs and benefits.

- Evaluation subsystem modules (ESY) that evaluate and rank countermeasure strategies, i.e., combinations of countermeasures based on their potential benefit and the preferences of the decision makers.

The ESY (Fig. 1) provides decision support by helping:

1. Formulate the decision problem.

2. Evaluate the strategies.

3. Appraise the decision process.

An early step in the formulation of the decision problem is to identify the objectives of the problem, i.e. what the decision makers are trying to achieve by taking a decision. Elicitation exercises [3,4] have been organised to investigate the attributes, i.e. the factors that the decision makers should take into account. The decision makers found it very difficult to articulate the factors that would drive their decisions in a nuclear emergency. Despite their difficulties an attribute tree was built during a Finnish elicitation exercise [4]. The attributes considered in the ESY are based on these findings. They differ depending on the phase of the nuclear emergency. This is because at later phases the decision makers will have more time to consider more attributes and balance the short with the long-term consequences of the strategies over different age groups.

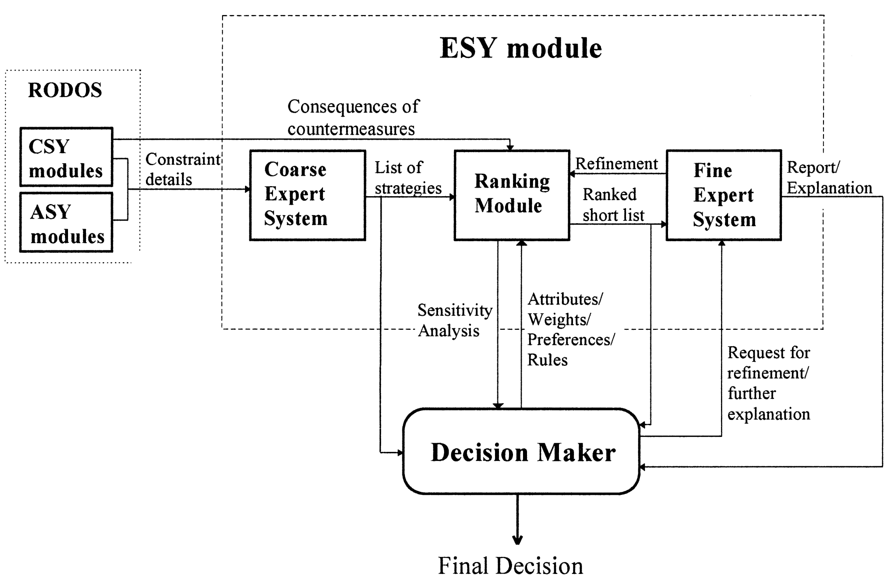

Fig. 1. An overview of the ESY.

A significant step in the formulation of a decision problem is the identification of the alternatives. In this study, alternatives are the strategies that impose different countermeasures in the contaminated by radiation areas. There are decision problems where it is very hard even to find one alternative. However, nuclear emergencies fall into a category of decision problems where the number of alternatives is very high. In order to decrease the number of alternative strategies to a manageable fraction, a coarse expert system [5] has been developed. This expert system encodes constraints in the form of desirable characteristics of strategies or in the form of practicality rules. Strategies that fail to satisfy the constraints are rejected.

After supporting the decision makers in the formulation of the decision problem by identifying feasible strategies and suggesting appropriate attributes, the ESY provides decision support in the ranking of the strategies. It currently uses an additive value function to rank the strategies based on the weights elicited by the decision makers and the consequences of the strategies over the attributes as calculated by other countermeasure subsystem modules in RODOS. The ESY design allows an exponential multi-attribute utility function to be used to model the inherent uncertainties of a nuclear emergency. However, until we have further explored uncertainty issues with decision makers, this modeling has not been fully implemented nor tested. Sensitivity analysis is conducted on the weights of the attributes to find out how they affect the ranking of the strategies.

The output of the ESY is a ranked short list of the best 10 strategies. In order to add transparency into the evaluation process and appraise the final ranking, the ESY uses the fine expert system (Fig. 1) to generate a natural language report [6] explaining why a strategy was preferred over another. This is crucial for the acceptance of the results of the system. It has been shown [7] that the dogmatic advice of a decision support system is very likely to be rejected even if it is mathematically correct. Apart from providing sound advice, the ESY should also justify its reasoning.

3. Generating feasible strategies

3.1. Constraints

The coarse expert system facilitates the search for good alternative strategies, which could be carefully evaluated later. The first step in this process is to decide which factors (see Table 1) the decision makers should take into account when selecting the strategies. Attributes can then be defined to measure the level of achievement of a strategy on each factor. Finally, we define the criteria that determine the inclusion of a strategy or its exclusion from the decision process. The criteria or constraints considered in this study for the early phases of a nuclear emergency (hours or days after the radiation accident) are outlined below.

3.1.1. Evacuation countermeasure constraint

Evacuation in nuclear emergencies refers to the removal of population from an area in order to avoid relatively high short-term exposures to radiation. This countermeasure

Table 1
Criteria used in the preselection process

Factor	Attribute	Constraints / Criteria	
		for inclusion	for exclusion
Feasibility of evacuation	Time needed to evacuate an area	Strategies where time needed for the evacuation $\leq$ minimum estimated time for safe evacuation	Strategies where time needed for the evacuation $>$ minimum estimated time for safe evacuation
Intervention Levels	Level of averted dose	Strategies with averted dose $<$ Low intervention level	Strategies with averted dose $>$ Upper intervention level
Continuity of treatment	Location of an area with respect to neighbour areas where action is taken	Strategies which take action in a continuous way i.e. both to areas close and far away from the source of radiation	Strategies which take action in areas located far away from the source of radiation and not at neighbour areas close to the source of radiation
Direction of release	Areas affected by the plume of radiation	Strategies which apply countermeasures to areas where the plume of radiation passes over	Strategies which apply countermeasures to areas not affected by radiation
Feasibility of countermeasures. Resources and infrastructure available	Feasibility of countermeasures or combinations of countermeasures	Example: Strategies that impose the distribution of iodine tablets only in areas where there is the manpower and the infrastructure to do so	Example: Strategies which impose evacuation and sheltering simultaneously at the same area

has the potential to prevent all exposure to a release if it is carried out before the release. However, it can result in high doses if it is incorrectly implemented. If it is implemented after the release, partial exposure to radiation can be expected. More specifically, while people are being evacuated, they are protected less against radiation than if they sheltered inside solidly constructed buildings. For that reason, people should be evacuated during or after a release only if they receive less dose than they would receive if other countermeasures were applied.

3.1.2. *Intervention levels constraint*

These encode international and national guidance [8] on when it is appropriate to implement a countermeasure. They are defined as levels of averted dose at which a particular countermeasure should be taken. They can be used in conjunction with action levels, which are usually levels of contamination above which action should be taken. If a two-tier system of intervention levels [9] is adopted then a particular countermeasure should be implemented if it could avert dose more than the upper intervention level. On the other hand, if a countermeasure averts less dose than the lower intervention level then it should not be taken. If the averted dose is between the two levels, then the decision is left to the discretion of the emergency managers. It should be noted that intervention levels are used in the development of emergency plans and provide broad guidance on intervention decisions rather than determining the best strategy.

3.1.3. Continuity of treatment constraint

Neighbouring populations should be treated in a continuous way during a nuclear emergency. If countermeasures are applied to areas far away from the nuclear plant then the same or more effective measures should be taken for people living closer to the source of the release. It should be noted that in some cases this might not be necessary. For example, at the time of the release, due to some meteorological conditions, the plume of radiation may rise steeply and not contaminate the area close to the nuclear plant. However, the same plume may contaminate heavily some areas far away from the plant. In that case, purely radiological arguments would justify the implementations of measures only for the areas that are affected. This is not advisable, though, because people living close to the release point would never understand nor accept this and so become subject to stress.

3.1.4. Direction of release constraint

The most influential meteorological factor in nuclear emergencies is the wind. The wind direction in particular determines how the plume of radiation will spread and which areas it will affect. There is no need in general to apply countermeasures to those areas that will not be affected by the plume. This is because taking measurements can have a major disruptive effect to the personal and professional lives of individuals and it should be avoided when it is not necessary.

3.1.5. Feasibility of countermeasures constraint

In nuclear emergencies, some strategies may be infeasible because they do not satisfy some time constraints. For example, it is not possible to issue iodine tablets to people who have already been evacuated. Another factor that should be taken into account is the availability of any resources and infrastructure for implementing a countermeasure. If there is not such infrastructure then the countermeasure cannot be implemented.

The users can select or deselect any of the criteria through an interface. They can also modify the criteria by changing their associated parameters, e.g. the intervention levels. A strategy is decided to be worth further evaluation if it satisfies the criteria for inclusion. These criteria can be treated as constraints. The problem of identifying feasible strategies is therefore a constraint satisfaction problem. The coarse expert system rejects those strategies that do not satisfy the given constraints. It should be noted that the above constraints are examples. Other types can be coded in — for instance, it would be possible to consider scheduling the order of evacuation in different areas and constraints upon that aspect of the planning. Using constraint satisfaction techniques can reduce significantly the number of strategies to be considered for evaluation. A detailed description of the methodology is given in Ref. [5].

Some strategies may have side effects or negative consequences that may inhibit the actions of a decision maker. Risk is often associated with the entire spectrum of negative side effects and their associated probabilities. An advantage of imposing constraints on high negative effects is that we eliminate or reduce the probability of these serious side effects occurring and therefore the risk linked with them.

3.2. Modelling

At the early phases of a nuclear emergency, the countermeasures that the decision makers could take into account are:

- Issue of iodine tablets

- Sheltering (in houses or emergency centers)

- Evacuation

The number and type of countermeasures differs considerably. Some countries only consider evacuation as a protective action and there may be no provision of iodine tablets in some areas. At the medium phases, potential countermeasures could be to relocate the population, decontaminate or take agricultural countermeasures such as food bans, processing and storage of food, removal of animals and replacement of foodstuffs in animals.

The area around the nuclear plant is divided into emergency planning zones and sectors which form sub-areas called blocks (see Fig. 2). In this example, there are 17 blocks. The number of sectors and zones and, indeed, their shape varies between different European countries. A countermeasure can be implemented throughout a block.

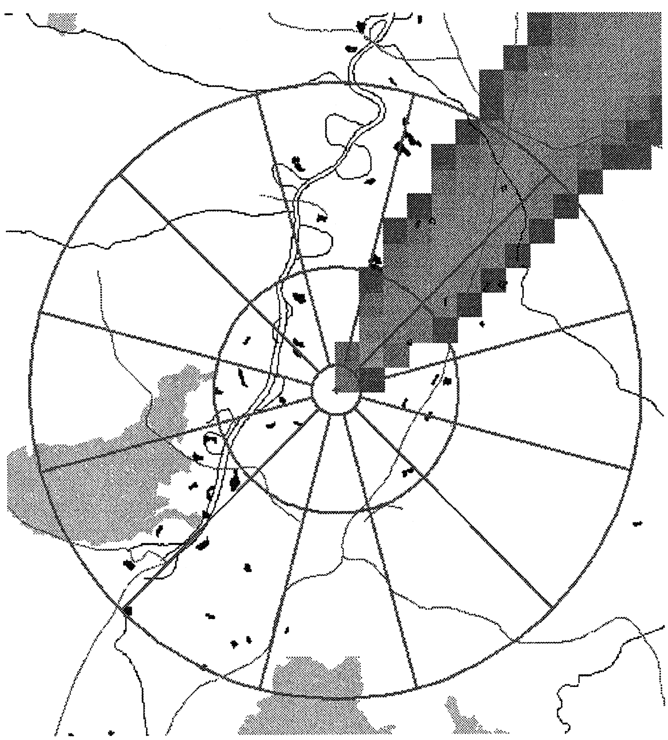

Fig. 2. Emergency planning blocks.

If a village or town lies between two sub-areas, then the blocks can be re-adjusted so that it is included in one block only. A strategy applies a countermeasure or a combination of countermeasures to each block. The option 'do nothing' in a block is also available.

4. The evaluation process

4.1. Consequence assessment

The severity of the health effects after a radiation accident depends upon two factors: the composition of the source term and the quantity of the radionuclides released. Radiation can affect irradiated individuals (somatic effects) or their descendants (hereditary effects). Somatic effects fall broadly into two broad categories: non-stochastic and stochastic. Non-stochastic effects occur when individuals are exposed to high levels of radiation usually shortly after a release of radioactivity. Stochastic effects can appear long after irradiation and the probability of them occurring is a function of dose without a threshold.

Many factors determine the non-stochastic effects such as the amount of dose that a person receives, the dose accumulation, the organs that are exposed and the exposure pathway. A linear dose–response relationship (linearity hypothesis) can be used to calculate the number of stochastic effects in an irradiated population [10]. Individual risk is measured by calculating a quantity known as the effective dose equivalent. However, this quantity is not suitable for expressing risks of high levels of radiation. This is because, there may be cases where individuals receive high doses on particular organs that result in non-stochastic effects while their effective dose equivalent calculated as the sum of the equivalent doses they received in all their tissues and organs might not rise any concerns. For this reason, non-stochastic effects are calculated in RODOS using hazard functions [11].

In this study, we assume that in a nuclear emergency most people will be exposed to low doses of radiation and that they will suffer from stochastic effects. The RODOS system uses different countermeasure subsystem modules to predict the health effects at the early phases of the nuclear emergency [12] when there are a lot of uncertainties in the estimation of the consequences and calculate the health effects at the medium phases [13] when there are enough deposition measurements. It also contains other modules to calculate the costs of implementing any countermeasures and to find optimum evacuation routes at the early phases [12].

4.2. Attributes

The attributes taken into account when taking a decision can be structured to hierarchies called attribute trees. The ESY will provide default attribute trees to the decision makers depending on the phase of the nuclear emergency. These default trees will be decided prior to the installation of the RODOS system in each country. As previous elicitation exercises have shown, differing groups of decision makers take into account different attributes depending on their culture, experience, background and interests. At the early phases, an attribute hierarchy could have the form of Fig. 3. The main objective is to return to normal living conditions. More analytically the attributes are as follows.

- Individual dose: This is the individual effective dose equivalent. Although collective dose (see below) seems to be the primary concern of the decision makers, this is still an important attribute.
- Collective dose: This is the sum of the individual doses over a population. Decision makers were particularly interested in this attribute during the elicitation exercises.
- Population number: The number of people potentially affected by the radiation accident and involved in a strategy. Because it is hard to measure the public acceptability of a strategy, the stress caused to the affected population and the feasibility of the countermeasures at the early phases of a nuclear emergency, this attribute is used instead. It can be seen as a proxy variable i.e. an attribute used because of its perceived relationship to the objective.
- Cost: Few decision makers have considered it at all in exercises and none have done so significantly. Nonetheless, we have included cost in the model for completeness.

Other attributes that might be of interest to the decision makers are the number of thyroid cancers or other related cancers, the technical feasibility of implementing a strategy and other political issues. Elicitation exercises are being organised to identify attributes for the medium phases of a nuclear emergency. Potential attributes for these phases are different types of doses like the individual and collective doses, thyroid and effective doses received by or averted in different age groups (e.g. adult, 1 year old, 10 years old) over several periods of time (e.g. 1 year after the accident, 5 years or 50 years ahead).

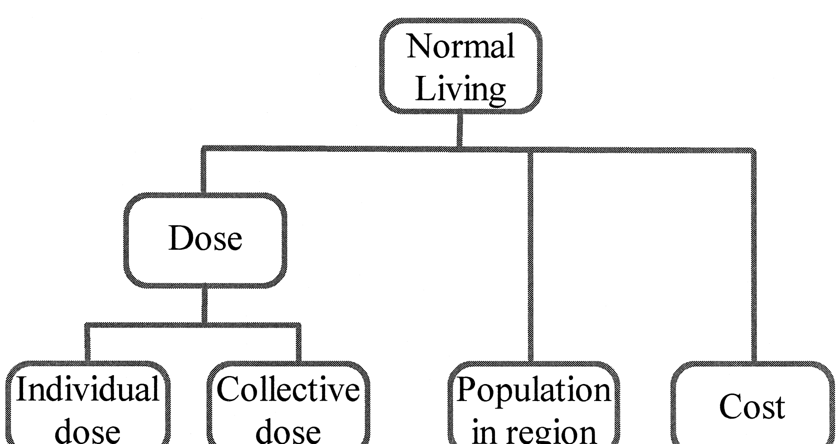

Fig. 3. An attribute tree.

4.3. Multi-attribute value or utility function

The ranking module evaluates and ranks alternative strategies using a linear multi-attribute value function:

$$v(x_1, x_2, \dots, x_q) = \Sigma_q^{i=1} w_i x_i \tag{4.1}$$

where x_i is the score of the strategy on the ith attribute and w_i is the weighting factor of the ith attribute. The ranking module performs a detailed sensitivity analysis by allowing the user to vary the w_i and observe the change in the ranking.

Value functions assume that the attribute values are known with certainty. This means that any uncertainty information is ignored. In order to deal with uncertainty we need to adopt a multi-attribute utility functional form. A multi-attribute utility function, $u(x_1, x_2, \dots, x_q)$, would rank a strategy according to its expected value:

$$E_{X_1, X_2, \dots X_q}\left(u(X_1, X_2, \dots X_q)\right) = \int u(x_1, x_2, \dots, x_q) \mathrm{d}x_1, \mathrm{d}x_2, \dots, \mathrm{d}x_q \tag{4.2}$$

where the expectation is taken with respect to the joint distribution of $X_1, X_2, \dots, X_q$ as reported by other modules in RODOS.

Noting that, at least in the early releases of RODOS, the joint distributions will either be reported as normal or in forms that may be approximated by normal distributions we choose the form of $u(\cdot)$ to make the expectation easy to calculate. The form we have chosen incorporates a single parameter reflecting risk aversion in addition to the weights within the linear value function. We use an exponential utility transform of $v(x_1, x_2, \dots, x_q)$:

$$\begin{aligned} u(x_1, x_2, \dots x_q) &= 1 - \mathrm{e}^{\frac{-v(x_1, x_2, \dots x_q)}{\rho}} \\ &= 1 - \mathrm{e}^{-\frac{\Sigma q_{i=1} w_i x_i}{\rho}} \end{aligned} \tag{4.3}$$

The utility function satisfies mutual utility independence [1] between all subsets of attributes and it is thus equivalent to the multiplicative multi-attribute utility function studied, inter alia, by Ref. [14] and used extensively in applications. The exponential transform implies constant risk aversion [14] but it seems likely to us that the decision makers should be risk averse in emergency management situations. Moreover, there are well-documented ways of assessing ρ [14,15].

The expectation of this functional form is very easy to take with respect to the normal distribution. Essentially one notes that the expectation has the same functional form as the normal moment generating function. If $(X_1, X_2, \dots, X_q)^{\mathrm{T}} \sim N(\boldsymbol{\mu}, \mathbf{V})$, i.e. are normal with mean vector $\boldsymbol{\mu}$ and covariance matrix $\mathbf{V}$, then it can be shown that:

$$E_{X_1, X_2, \dots, X_q}\left(u(X_1, X_2, \dots, X_q)\right) = 1 - \mathrm{e}^{-\left(\frac{\Sigma w_i \mu_i}{\rho} - \frac{\mathbf{w}^{\mathrm{T}} \mathbf{V} \mathbf{w}}{2\rho^2}\right)} \tag{4.4}$$

where $\boldsymbol{w}$ is the vector formed from the weights w_i and μ_i the mean score of the strategy on the ith attribute.

[1] X is said to be *utility independent* of Y if preferences between lotteries with varying levels of X and a common, fixed level of Y are independent of that fixed level of Y.

Noting that exponentiation is monotonic, this means that strategies should be ranked according to:

$$\sum_{i=1}^{q} w_i \mu_i - \frac{\boldsymbol{w}^{\mathrm{T}} \mathbf{V} \boldsymbol{w}}{2\rho} \tag{4.5}$$

In other words, strategies will be ranked by a linear function with weights w_i applied to the mean score of the strategy on the ith attribute with a term subtracted from the total score that depends upon the covariance matrix associated with the strategy. The more uncertain one is of the scores derived from the strategy the larger the term subtracted. Another point that should be noted is that if all strategies give rise to the same uncertainty as encoded by the covariance matrix **V**, the ranking is given simply by the first term: a linear form.

In the ranking module, we can use the utility function forms (4.1) and (4.3) to rank the strategies. The risk attitude parameter ρ may be subjected to sensitivity analysis along with the w_i parameters. We have not incorporated the form (4.4) yet. This is partly because the countermeasure subsystem modules in RODOS currently calculate the mean μ but not the variance V, and partly because we are still exploring with decision makers how to address the issue of uncertainty.

4.4. Generating a natural language report

Providing explanations in a decision support system is of paramount importance. In nuclear emergencies in particular, the decision makers will be people with different backgrounds ranging from scientists to politicians. Not all of them can understand the mathematical model used in the ESY for the ranking of the strategies. If no explanations were given then the decision makers would be likely to reject the recommendation of the system simply because they could not understand it.

The ESY uses an expert system which we call fine expert system to provide explanation facilities. It is a fairly simple natural language generator. It first decides the structure of the paragraphs and it then generates the text of the sentences using templates. Slots in the templates are filled in dynamically with the names of the strategies, the names of the objectives or some semantic quantifiers. For a detailed description of how the ESY justifies its advice see Ref. [6].

5. Results

5.1. Nuclear accident scenario

Suppose that there is a nuclear accident. The technical crisis teams have analysed the situation and have concluded that a release of radioactivity is expected to start in 4 h time. The area around the source of the release is divided into 17 blocks with the source at the center of the 'spider's web' (Fig. 4).

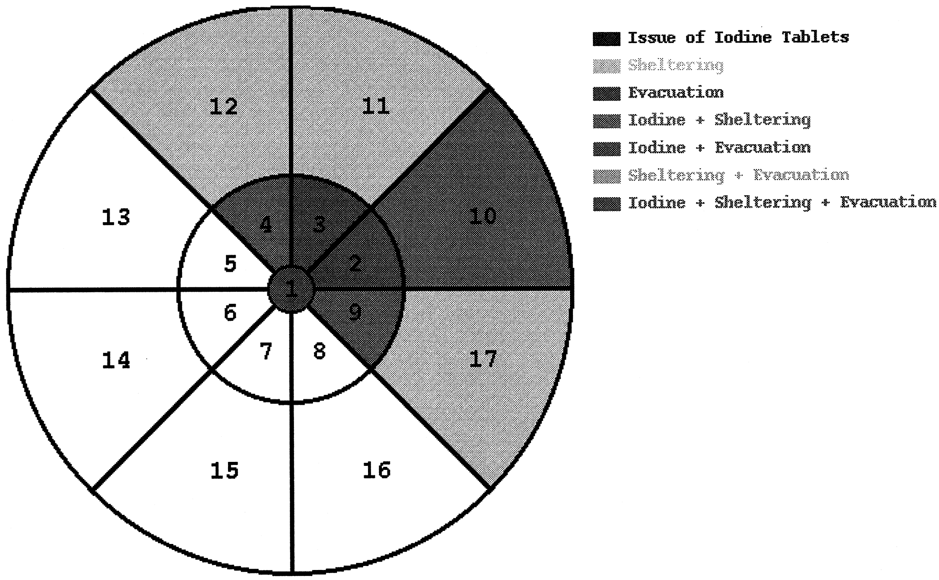

Fig. 4. Graphical display of a strategy.

If we consider 3 early phase countermeasures (issue of iodine tablets, sheltering and evacuation) then there are 2^3 combinations of countermeasures that we can apply to each block. Because in this example there are 17 blocks there are 2^{3*17} strategies to consider in total. Analysing subsystem modules in RODOS predict that the plume of radiation will affect blocks 1, 2, 3, 4, 9, 10, 11, 12 and 17 (see Fig. 4). The population distributions and evacuation rates in the blocks affected by the radiation can be seen in Table 2. The evacuation rates indicate how quickly an area can be evacuated and whether evacuation can be implemented without any people being exposed to high

Table 2
Population distribution and evacuation rates in the areas affected by radiation

Block	Population[a]	Evacuation rate[b]
1	300	300
2	8878	1500
3	1432	1000
4	1707	700
9	4378	1000
10	12 457	1700
11	7566	1000
12	4230	1200
17	657	1000

[a] Number of people in each block.
[b] Number of evacuated people per hour.

Table 3
Start time and duration of each countermeasure

	Iodine tablets (h)	Sheltering (h)	Evacuation (h)
Start time	0	0	0
Duration	0	720	168

levels of radiation. The start time and the duration of each countermeasure (Table 3) are user-defined parameters in RODOS. We consider 0 to be the current time. We assume that issuing iodine tablets is instant. This happens for example when the tablets are available at home.

According to the regulations composed by the International Commission on Radiation Protection (ICRP) an intervention can be justified by considering the averted average individual dose for the exposed to radiation population [8]. The intervention levels that justify a course of action might vary in different countries. In this example, we use a two-tier system of intervention levels (see Table 4) as suggested by the National Radiological Protection Board (NRPB) in the UK [16] but we have set the values of the intervention levels in accordance with the regulations of the ICRP which is an international body. If a countermeasure averts dose higher than the upper intervention level then it is almost always justified to apply it. ICRP also suggests that the decision makers should find an optimised low intervention level for each countermeasure with values no more than a factor of 10 lower than the values of the upper intervention level [8]. In this example, the values of the low intervention are exactly 10% lower than the corresponding values of the upper intervention level. The averted doses in each block and for each countermeasure can be found in Table 5.

5.2. Generation of feasible strategies

The coarse expert system applies the constraints and it reduces the number of strategies from 2^{51} to 144. A description of each strategy is given in text form. For example, strategies 56 and 140 are:

```
Strategy: 56/144
Block  1 : Issue of iodine tablets and evacuation
Block  2 : Issue of iodine tablets and evacuation
Block  3 : Issue of iodine tablets and evacuation
Block  4 : Sheltering
Block  5 : --
Block  6 : --
Block  7 : --
Block  8 : --
Block  9 : Issue of iodine tablets
Block 10 : Issue of iodine tablets and sheltering
Block 11 : Issue of iodine tablets and sheltering
Block 12 : Sheltering
Block 13 : --
Block 14 : --
Block 15 : --
Block 16 : --
Block 17 : --
```

```
Strategy: 140/144
Block  1 : Issue of iodine tablets and evacuation
Block  2 : Issue of iodine tablets and evacuation
Block  3 : Issue of iodine tablets and evacuation
Block  4 : Issue of iodine tablets and sheltering
Block  5 : --
Block  6 : --
Block  7 : --
Block  8 : --
Block  9 : Issue of iodine tablets and sheltering
Block 10 : Issue of iodine tablets and sheltering
Block 11 : Sheltering
Block 12 : Sheltering
Block 13 : --
Block 14 : --
Block 15 : --
Block 16 : --
Block 17 : Sheltering
```

Table 4
Intervention levels

Countermeasure	Low intervention level (mSv)	Upper intervention level (mSv)
Issue of iodine tablets[a]	50	500
Sheltering[b]	5	50
Evacuation[c]	50	500

[a]Averted equivalent dose to thyroid.
[b]Averted effective dose <1 day.
[c]Averted effective dose <1 week.

The strategies can also be seen through a graphical user interface. Different countermeasures or combinations of countermeasures are depicted by different colours. Strategy 140 can be seen in Fig. 4.

5.3. Evaluation of the strategies

The 144 strategies generated by the coarse expert system are passed into the ranking module and evaluated based on their consequences as calculated by the countermeasure subsystem modules and the weights given by the decision makers. In order to compare the strategies on the individual attributes, we need to find some meaningful scores. Instead of comparing consequences over the attributes such as doses and cost (e.g., 11 mSv and 1.2 Mega-ECU) we can scale these values so that the strategy with the worst consequence takes the score 0 while the strategy with the best consequence takes the score 100. For example, if the most expensive strategy to implement is strategy A with cost $x^* = 2.0$ Mega-ECU and strategy B is the cheapest one with cost $x^0 = 1.0$

Table 5
Averted dose if a countermeasure is implemented

Blocks	Iodine tablets[a] (mSv)	Sheltering[b] (mSv)	Evacuation[c] (mSv)
1	810.1	233.2	1167.3
2	567.9	163.4	817.2
3	540.7	132.8	799.4
4	187.4	38.8	90.3
9	150.3	37.6	102.5
10	387.6	70.7	350.8
11	320.9	74.8	370.4
12	42.3	22.5	45.9
17	39.7	10.2	30.9

[a]Averted equivalent dose to thyroid.
[b]Averted effective dose in a day.
[c]Averted effective dose in a week.

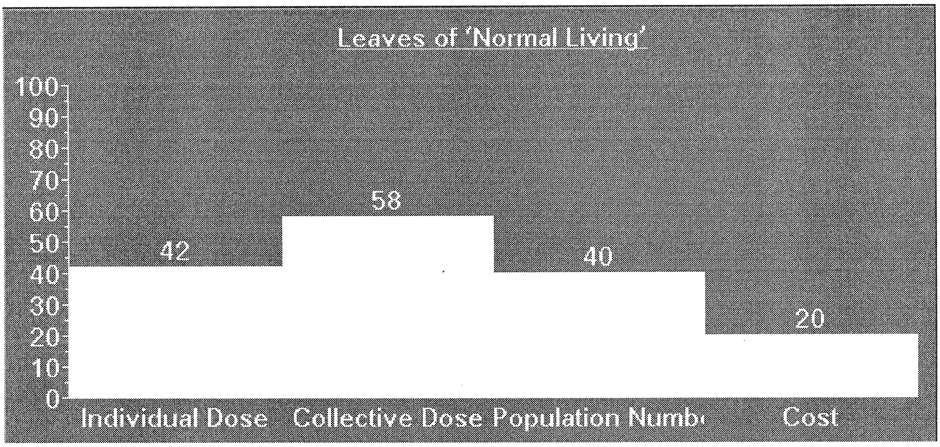

Fig. 5. Weights of the attributes.

Mega-ECU then strategy A takes the score 0 and strategy B takes the score 100. Any other strategy i costing x_i Mega-ECU takes the score:

$$s_{\text{cost}}(x_i) = \frac{x_i - x^*}{x^* - x^0}$$

Scaling the consequences of the strategies makes their scores on the attributes to be more directly comparable. Using the above formula however, has the disadvantage that we assume that 1.5 Mega-ECU is exactly halfway between 1.0 Mega-ECU and 2.0 Mega-ECU. This means that the value of increasing the cost of a strategy from 1.0 to 1.5 Mega-ECU is equal to the value of an increase from 1.5 to 2.0 Mega-ECU. Yet, there might be some decision makers who do not agree with that. For this reason, we are

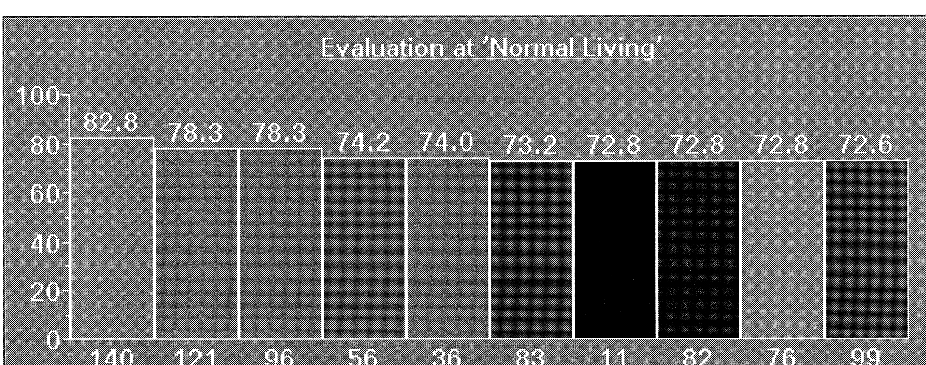

Fig. 6. Displaying the 10 best strategies.

planning to add to the ESY an interface where the decision makers will be able to draw or determine their value functions over the consequences of the strategies.

The ESY does not provide any facilities to elicit the weights w_i of the attributes and the risk attitude parameter ρ from the decision makers. The weight of an attribute is an important decision parameter because it indicates how important the attribute is for the decision makers. It has been shown [17] however, that the information presented to the decision makers and the questions being asked to elicit their preferences can influence their decisions. Using a computer package could require from the decision makers to input their preferences in a restrictive way and even make them biased because of the framing of the questions asked. Besides, if preference elicitation techniques were to be

FES Report

`Strategy 140` vs. `Strategy 56`

Return_to_Normal_Living

`Strategy 56` provides slightly worse *Return_to_Normal_Living* than `Strategy 140`.

- This judgement takes into account the effects of *Decrease_of_Dose*, *Decrease_of_Population_Involved* and *Reduction_in_Cost*.
- While *Reduction_in_Cost* is the main reason to prefer `Strategy 56`, this is outweighed by considerations of *Decrease_of_Dose*, along with other less important factors, that provide motivation for preferring `Strategy 140`.

Decrease_of_Collective_Dose

Decrease_of_Collective_Dose is a compelling factor favouring `Strategy 140` over `Strategy 56`.

- The importance of *Decrease_of_Collective_Dose* in determining *Return_to_Normal_Living* is so great that the relatively small difference between `Strategy 140` and `Strategy 56` is nevertheless significant in this case.
- `Strategy 140` provides reasonably better *Decrease_of_Collective_Dose* than `Strategy 56`. `Strategy 140` provides very good *Decrease_of_Collective_Dose* in the context of all available strategies. `Strategy 56` provides neither very good nor very poor *Decrease_of_Collective_Dose* in the context of all available strategies.
- `Strategy 140` rates 84 relative to *Decrease_of_Collective_Dose* on a scale from 0 to 100. `Strategy 56` rates 70 relative to *Decrease_of_Collective_Dose* on a scale from 0 to 100.
- *Decrease_of_Collective_Dose* accounts for 58 percent of the determination of *Decrease_of_Dose* and 36.2 percent of the determination of *Return_to_Normal_Living*.

Fig. 7. FES Report.

introduced in the ESY then the decision process would become complicated and time-consuming and this could discourage users form using the system. We therefore assume that the weights and the risk attitude parameter are elicited away from the ESY — for example in a Decision Conference prior to the installation of RODOS into a country — and then are fed back to it. The decision makers however can see the effects of the weights by using the sensitivity analysis tools provided by the ESY. The explanation report also gives insight into the way that the weights influence the final ranking of the strategies and helps the decision makers to refine their weights and any other decision parameters.

After calculating the scores of the strategies relative to the attributes we calculate an overall score for each strategy using either the formula 4.1 or 4.3. In this example we have used the additive value function (Eq. (4.1)) and the weights of Fig. 5. The higher the overall score the better or more preferred the strategy is. The 10 strategies with the highest scores are displayed to the decision makers (Fig. 6). Strategy 140 is considered to be the best one. This does not mean that the decision makers should necessarily choose it. They can conduct sensitivity analysis to find how robust the 10 best strategies are or read the explanation report. Then they can choose the strategy they are most comfortable with.

5.4. Report

The ESY can generate a report explaining why a strategy was preferred over another relative to any attributes. In this example, we give an extract of the report which explains why strategy 140 is better than strategy 56 (see Fig. 7).

5.5. ESY assessment

A preliminary questionnaire [18] has been recently distributed to assess the utility of the ESY. The system scored very satisfactorily in terms of performance, usefulness and other criteria. The results are quite encouraging. Further evaluation and analysis are currently under way.

6. Related work

Other systems that evaluate strategies in nuclear emergencies fall broadly into two categories: evaluation systems for the early phases of a nuclear emergency and evaluation systems for the later phases. They use a variety of methods ranging from rule-based systems to multi-attribute value and utility theory.

(1) CMDSS (*C*risis *M*anagement *D*ecision *S*upport *S*ystem) [19] is a computer-based decision support system for the evaluation of countermeasures, i.e. combinations of activities that can reduce the ingestion dose form contaminated foodstuffs. CMDSS is tailored to Switzerland's legal system for handling nuclear emergencies.

(2) DACFOOD [20] provides decision support when there is contamination on foodstuffs caused by radiation. It uses a rule-based system where the knowledge is represented in

terms of assertions, i.e. actions (e.g. milk destruction) and observations (e.g. low contaminated milk) as well as clauses that illustrate the logic dependencies between the assertions.

(3) M-Crit [21] [22] is another evaluation system developed in RODOS. Contrary to the ESY, it makes the assumption that the decision makers are sure of their preferences and it tries to articulate their value judgements using an interactive implementation of the piecewise linear approximation method.

(4) MOIRA (*Mo*del-Based Computerised System for Management Support to *I*dentify Optimal *R*emedial Strategies for Restoring Radionuclide Contaminated *A*quatic Ecosystems and Drainage Areas) [23] is a decision support system that will assist decision making on aquatic ecosystems contaminated by radioactive fallout. The system evaluates strategies that have the potential to restore contaminated water systems like lakes.

(5) NCSR's (*N*ational *C*enter for *S*cientific *R*esearch) evaluation system for pre-release countermeasures [24] identifies an optimum combination of protection actions at the pre-release phase of a radiation accident. It can work in the presence of conflicting objectives and under uncertainty concerning the release of radioactivity and the weather conditions.

(6) NCSR's evaluation system for long term countermeasures [25] assists decision making in determining long term protective measures such as improvement of living conditions and relocation after a severe nuclear accident. The decision makers are given only those strategies that are efficient and they can interact with the system to reach a decision.

(7) Penry and Vanderpooten [26] describe a system for supporting decision making at the medium phases of a nuclear emergency. Agriculture countermeasures such as decontamination, processing, destruction and preservation can be mixed to form a strategy (e.g. 30% of milk is destroyed and the remaining 80% is decontaminated). The decision makers can interact with the system to restrict the set of the efficient strategies or optimise a preferable strategy.

(8) PRANA DSS (*D*ecision *S*upport *S*ystem for the *P*rotection and *R*ehabilitation of the *A*grosphere after a *N*uclear *A*ccident) [27] is a decision support system for the assessment of long-term countermeasures such as food bans, relocation of the population and other agricultural countermeasures in rural areas. It provides a variety of information such as demographic and monitoring data, intervention levels and maps of the area.

(9) RADE-AID (*R*adiological *A*ccident *DE*cision *AID*ing) [28] is a decision support system that helps the decision makers in the formulation of decisions concerning the application of countermeasures such as agriculture measures and relocation after a radiation accident.

(10) SOPA (*S*elects *O*ff-Site *P*rotective *A*ctions) [29] is a model for the selection of off-site protective actions such as evacuation and sheltering during nuclear accidents. The model takes into account both radiological and non radiological risks, i.e. risks of evacuation as well as weather conditions, actual releases and the status of the physical plant and it can be used under uncertain circumstances.

Only a few evaluation systems incorporate a systematic approach for generating and screening alternative strategies. SOPA [19] generates all the possible combinations of activities. A panel of experts then screen out all the combinations that are infeasible or inefficient. Papazogou and Christou [24] and Papazoglou and Kollas [25] use an algorithm based on dynamic programming to determine the efficient set of the alternatives whereas Perny and Vanderpooten [26] employ a scalarizing function derived from the Tchebychev norm for the same purpose. The ESY proposes constraint programming as an alternative approach for identifying good strategies, worth further evaluation. Constraint programming models the problem of generating strategies in a natural way and it has proved to be very efficient [5].

Most evaluation systems use multi-criteria decision analysis techniques for the evaluation of the alternatives. The ESY employs the multi-attribute value theory model whose use in radiation protection has been recommended by the ICRP [30]. With the exception of CMDSS, which outputs a short description of the strategies suggested, no explanation facilities are provided by the other evaluation systems. The ESY not only outputs a list of the ten best strategies but it also justifies its advice and explains why a strategy is preferred to another. The explanations given by the system add transparency into the decision analysis process. If a decision maker is not satisfied with the explanation provided, she can refine the decision model. In other evaluation systems, the decision makers may have to spend considerable time in assessing the decision parameters whereas in the ESY they can start with a predefined set of parameter values such as the weights of the attributes and then refine them as many times as they want during the evaluation process.

Finally, most evaluation systems are intended to be used under specific circumstances. The ESY, however, is designed to operate throughout all the phases of a nuclear emergency providing advice on both early phase countermeasures such as evacuation and sheltering as well as agriculture countermeasures.

7. Conclusions

The main aim when applying a strategy in a nuclear emergency is to eliminate or mitigate any adverse health effects. However, the implementation of a countermeasure can cause social and economic disruption and it might entail some risk to the population affected and the workers involved. For this reason, the implementation of a strategy would only be justified if its benefits in terms of reduced health effects outweighed its disadvantages which include its financial cost and the social disruption that the strategy causes. The ESY uses a multi-criteria decision analysis methodology to rank the strategies and it helps the decision makers to balance their objectives. A short list of the ‘optimum’ 10–15 strategies is provided.

Even if a strategy is justified it cannot still be implemented if it is infeasible or if intervention is not advised given the conditions of the nuclear accident. For example, there might be protective actions with positive net benefit despite averting dose below the low intervention level. Moreover, there might be strategies which are justified but cannot be applied for practicality reasons. The ESY screens out all those strategies which are clearly inferior and evaluates only those that have the potential to be implemented. Given that the number of strategies to consider can be very high, this screening process has the advantage of decreasing considerably the number of alternatives and therefore reducing the evaluation time.

Decision making in nuclear emergencies should be transparent. The decision makers will have to justify their actions to the public after a radiation accident. They would never accept the dogmatic recommendation of any decision support system. In order to make the decision makers trust the results of the ESY we have incorporated explanation facilities into the system. A natural language report is generated explaining why a strategy is preferred over another. Work is under way to explain the sensitivity analysis results and give an overview of the best strategies.

The ESY provides a variety of tools to support decision making in nuclear emergencies. It helps the decision makers not only in the evaluation of the alternative strategies but also in the formulation and appraisal of the decision problem. More precisely, the ESY identifies feasible alternatives worthy of further evaluation and eliminates those strategies that have high negative side effects. Then the system ranks the strategies using a multi-attribute value function. A multi-attribute utility function can also be used to model the risk attitudes of the decision makers. The sensitivity of some decision parameters such as the attribute weights can be tested using sensitivity analysis tools. Finally, the system adds transparency into the way it ranks the strategies and justifies its advice by offering explanation facilities.

Acknowledgements

We are grateful to our colleagues in the RODOS project for their comments and suggestions throughout the development of the ESY. This work is funded by the Commission of the European Communities (Contract: F14P-CT95-0007). The views expressed in this paper are those of the authors and do not necessarily reflect those of the RODOS project.

References

[1] J. Ehrhardt, J. Brown, S. French, G.N. Kelly, T. Mikkelsen, H. Müller, RODOS: decision-making support for off-site emergency management after nuclear accidents, Kerntechnik 62 (1997) 122–128.

[2] S. French, K.N. Papamichail, D.C. Ranyard, J.Q. Smith,Design of a decision support system for use in the event of a nuclear emergency, in: F. Javier Giron, M. Lina Martinez (Eds.), Applied Decision Analysis, Kluwer Academic Publishers, Boston, pp. 2–18, 1998.

[3] S. French, J. Ehrhardt, J. Lochard, M. Morrey, K. Sinkko, A. Sohier, What sort of support is needed in nuclear emergency management? 5th International Conference of the Decision Sciences Institute, Athens, Greece, 1999, pp. 443–447.

[4] R.P. Hämäläinen, K. Sinkko, M. Lindstedt, M. Amman, A. Salo, RODOS and Decision Conferencing on Early Phase Protective Actions in Finland, Research Report STUK-159, STUK Radiation and Nuclear Safety Authority, Helsinki, Finland, 1998.

[5] K.N. Papamichail, S. French, Generating feasible strategies in nuclear emergencies — a constraint satisfaction problem, Journal of the Operational Research Society 50 (6) (1999) 617.

[6] K.N. Papamichail, Explaining and justifying decision support advice in intuitive terms, Proceedings of the 13th European Conference on Artificial Intelligence, Brighton, 1998, pp. 102–103.
[7] R.L. Teach, E.H. Shortliffe, An analysis of physician attitudes regarding computer-based clinical consultation systems, Comput. Biomed. Res. 14 (1981) 542–558.
[8] ICRP, Principles for intervention for protection of the public in a radiological emergency, Ann. ICRP 22 (1993) 4, ICRP Publication 63.
[9] M. Morrey, S. Haywood, J. Brown, N. Higgins, F. Fry, Intervention for recovery after accidents, Documents of the NRPB 8 (1) (1997) 3–20.
[10] ICRP, Protection of the public in the event of major radiation accidents: principles for practice, Ann. ICRP 14 (2) (1984) ICRP Publication 40.
[11] J. Ehrhardt, I. Hasemann, C. Matzerath-Boccaccini, C. Steinhauer, J. Raicevic, COSYMA: Health Effects Models, FZK Report 5567, Forschungszentrum Karlsruhe, Karlsruhe, 1995.
[12] J. Päsler-Sauer, T. Schichtel, The simulation of early emergency actions in RODOS, Radiat. Prot. Dosim. 73 (1–4) (1997) 71–74.
[13] J. Brown, K.R. Smith, P. Mansfield, J. Smith, Models for decontamination, relocation and agricultural countermeasures, Radiat. Prot. Dosim. 73 (1–4) (1997) 75–79.
[14] R.L. Keeney, H. Raiffa, Decisions with Multiple Objectives: Preferences and Value Tradeoffs, Wiley, New York, 1976.
[15] R.T. Clemen, Making hard decisions — an introduction to decision analysis, PWS-Kent, Duxbury Series, Boston, 1991.
[16] NRPB, Living with Radiation, National Radiological Protection Board, HMSO Publication Centre, London, 1989.
[17] A. Tversky, D. Kahneman, The framing of decisions and the psychology of choice, Science 211 (1981) 453–458.
[18] K.N., Papamichail, The Design of an Evaluation Module within RODOS and its Assessment, 5th International Conference of the Decision Sciences Institute, Athens, Greece, 1999.
[19] A.G.M. Schenker-Wicki, The Conceptual Definition of a Crisis Management Decision Support System CMDSS for Evaluating Acceptable Countermeasures to Reduce Ingestion Dose after an Accidental Release of Radioactivity, University Press Fribourg Switzerland, Fribourg, Switzerland, 1990.
[20] D. Soulatges, A. Despres, A. Diaz, DACFOOD: a decision support system in case of foodstuffs contamination, Presented at the Joint International Conference on Operational Research and Management Science, Helsinki, Finlad, 1992.
[21] A. Goloubenkov, D. Kamajev, J. Ustinov, Formation of the utility function taking into account uncertainties in expert preferences, RODOS Report RODOS(WG5)-TN(98)04, Federal Environment Emergency Research Centre Scientific Production Association ''Typhoon'', 1998.
[22] V. Borzenko, S. French, Decision analytic methods in RODOS, in: A. Karaoglou, G. Desmet, G.N. Kelly, H.G. Menzel (Eds.), The Radiological Consequences of the Chernobyl Accident, EUR 166544 EN, Office for Official Publications of the European Communities, Luxembourg, 1996, pp. 1149–1158.
[23] A. Appelgren, U. Bergström, J. Brittain, E. Gallego Díaz, L. Håkanson, R. Heling, L. Monte, An outline of a model-based expert system to identify optimal remedial strategies for restoring contaminated aquatic ecosystems: the project ''MOIRA'', Technical Report RT/AMB/96/17, Dipartimento Ambiente, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, 1996.
[24] I.A. Papazoglou, M.D. Christou, A decision support system for emergency response to major nuclear accidents, Nucl. Technol. 118 (1997) 97–122.
[25] I.A. Papazoglou, J.G. Kollas, Establishing protective long term measures after severe nuclear accidents using multiple criteria, Health Phys. 72 (5) (1997) 676–692.
[26] P. Perny, D. Vanderpooten, An interactive multiobjective procedure for selecting medium-term countermeasures after nuclear accidents, J. Multi-Criteria Decision Analysis 7 (1998) 48–60.
[27] B. Yatsalo, O. Mitzeabassov, I. Okrimenko, I. Pichugina, B. Kulagin, PRANA — decision support system for assessment of countermeasure strategy in the long-term period of liquidation of the consequences of a nuclear accident (agrosphere), Radiat. Prot. Dosim. 73 (1–4) (1997) 291–294.
[28] Wagenaar et al., RADE-AID: an operational tool for decision makers, Proceedings of the Seminar on

Methods and Codes for Assessing the Off-Site Consequences of Nuclear Accidents, Athens, Greece, 1990, pp. 577–612.

[29] S.D. Weerakkody, W.F. Witzig, A rational model for the off-site protective action selection during nuclear reactor accidents, Nucl. Technol. 78 (1) (1987) 43–53.

[30] ICRP, Optimisation and decision-making in radiological protection, Ann. ICRP 20 (1) (1989) ICRP Publication 55.