8. DECISION ANALYSIS OF PROTECTIVE ACTIONS IN FOREST AREAS

Kari Sinkko, Tarja K. Ikäheimonen and Raimo Mustonen
Finnish Centre for Radiation and Nuclear Safety
P.O. Box 268, SF-00101 Helsinki, Finland

A nuclear accident itself and the introduction of protective action entail risks to the people affected, monetary costs and social disruption. As far as the society is concerned the values which enter decisions on protective actions are multidimensional. People have strong feelings and beliefs about these values, some of which are not numerically quantifiable and do not exist in monetary form. These problems, often including mutually conflicting objectives and uncertainties and are difficult to control simultaneously, cannot be undertaken without careful consideration of the essential consequences of decisions. Decision analysis can be applied in planning intervention, this helps in rendering explicit and apparent all the factors involved and evaluating their relative importance. In this study recovery operations to clean up a forest environment in the event of a hypothetical radiation accident in a nuclear power plant were analyzed and discussed to determine what would be appropriate intervention levels in protecting the public, workers and the environment. The values considered essential in the decision were included in the analysis and their importance on decision making process is discussed.

8.1. INTRODUCTION

Situations in which the radiation sources, the pathways and the exposed individuals are already in place when decisions on remedial actions are considered, are called *intervention* situations. In these situations the doses which are received or are likely to be received can only be reduced by remedial actions. The basic principle when implementing of protective actions is that intervention should be *justified* and *optimized*, i.e., the introduction of a protective measure should achieve more good than harm and the net benefit should be maximized (IAEA91, ICRP91). Decision analysis is a suitable method for helping to solve societal problems of this type.

Research over the past 30 years has transformed the abstract mathematical discipline of decision theory to a potentially useful technology known as *decision analysis*, which can assist decision makers to handle large and complex problems together with their attendant flow of information. Decision analysis is not intended to solve problems directly. It's purpose is to produce insight and understanding. In the light of that understanding the decision maker can make better decisions. Those interested in the theory of decision analysis may consult the literature (Fr88, Go92, Ke76, Wi86). This report provides an application how decision analysis can be used when planning protective actions.

As initially presented the background information is generally limited or incomplete in decision making. A careful analysis of the problem indicates what further information is needed to find the best course of action. Thus the aim of this study was not only to find the best protective actions, but also to indicate the information that should be catered for or revised. If in the light of revised information or gained insight new, feasible actions are identified, the analysis should be revised.

The following analysis deals with protective actions for contaminated forest areas. The actions which most probably have to be taken on cultivated or natural foodstuffs, were excluded, although they might have had an effect on the analysis. Because of the high contamination levels considered in this study there would certainly be restrictions on the use of natural foodstuffs.

8.2. ACCIDENT SCENARIO

For the purpose of the analysis it was assumed that a hypothetical accident had happened at a nuclear power plant in Finland leading to a core melt and to a very severe - presumably worst possible - contamination of the environment (cf. chapter 3). 10% of fission products and 1% the transuranics were assumed to have released from a 700 MW BWR reactor. It was further assumed that the accident had happened in summer time and there had been only dry deposition. As a consequence of the accident the forest areas given in Table I were contaminated.

Table I. Fallout area in forest land and the contamination levels after a hypothetical reactor accident.

Nuclide	Area I 1.5 km^2	Area II 22 km^2	Area III 1660 km^2
^{137}Cs mean	> 100 MBq/m^2	10-100 MBq/m^2 20 MBq/m^2	1-10 MBq/m^2 2 MBq/m^2
^{90}Sr mean	> 77 MBq/m^2	7.7-77 MBq/m^2 15 MBq/m^2	0.8-7.7 MBq/m^2 1.5 MBq/m^2
^{239}Pu mean	> 22 kBq/m^2	2.2-22 kBq/m^2 5 kBq/m^2	0.2-2.2 kBq/m^2 0.5 kBq/m^2

8.3. CONCERNS AND ISSUES

From the radiation protection point of view the aim of protective actions is to reduce the individual as well as the collective doses to the public and workers, and also to reduce radiological impacts on the environment. Concerning the forest, the aim is also to keep the area in, or bring it back into production by feasible decontamination.

Intervention will affect the exposure pathways, and it should be carefully considered, that the total detriment of the population is reduced and, e.g., the dose is not reduced in one group by increasing it in another group. For example, the decontamination and the reduction of exposure to the population can be achieved only by increasing the doses to workers, who are carrying out the intervention measures.

The use of dose limits as the basis for the deciding on intervention might involve actions that would be out of all proportion to the benefit obtained and would thus conflict with the principles of justification and optimization. ICRP therefore recommends against the application of dose limits or any predetermined limits for deciding on the need for intervention. However, the position of workers carrying out recovery operations is different. These actions, non the less even they are in response to an accident, can be planned and optimized in advance and therefore it is recommended that workers undertaking recovery operations should be subject to the normal system of radiological protection and dose limits should be applied.

The intervention measures entail also non-radiological risks to the population and the workers caused by various kind of accidents. The risks which are directly associated with remedial actions should be taken into account when making decisions on intervention. In addition, there might be radiological risks caused, for example, by forest fires. Fires would result in the resuspension of radionuclides and an increasing number of individuals will be subject to radiation.

Psychological stress could lead to health effects of a comparable nature to those arising from the contamination and at the same time reduces the quality of life significantly. A majority of the population in a contaminated area may show varying degrees of stress reactions, but stress could also be a consequence of a protective action. Stress can be reduced by taking appropriate actions, such as actions which decrease the dose of population, but at the same time this would lead to an increase in exposure among the intervening workers.

Perceived risk, in addition of health effects, can have serious economical and social consequences, e.g., to the forest economy and industry. The public opinion and the perception of risk could result in consequences which reduce the benefit of actions or make their implementation impossible. For example, in a limited accident the population (and the forest industry) might not accept products made from wood grown in the contaminated area although, e.g., only bark and branches of the trees were contaminated and the contamination could be removed very efficiently. The industry might think that the risk of being discredited by using contaminated materials is too great, and thus refuse to use even slightly contaminated raw materials.

Individual people and families own 75% of forests in Finland and the average area of a forest estate is 0.35 km^2. Thus, there would be nearly 5000 private forest estates in the contaminated area considered in this study. Land owners would be worried about their property and incomes, and so there would be considerable stress within this group of people.

The fallout would reduce the value of contaminated land for decades, but it would also reduce the value and the quality of the surrounding areas. The reduction in quality of the environment would take place also in the vicinity of disposal sites and around power stations burning radioactive wood.

Remedial actions would cause monetary costs to the individual land owners, industry and the society. The costs would include transportation costs, loss of income, costs of the control of the area and costs of lost capital services. Also the question of reimbursing land owners for any remedial actions would arise. If any compensation is paid, either in full or in part, it means that the costs to individuals would now be costs to society. None the less, would the cost of action be a limiting factor? The economic impact of an accident may not be entirely negative. The activities may have positive effect on the economy, such as generation of employment or production of energy by burning wood produced in the contaminated area.

8.4. DECISION MODEL

8.4.1. Action alternatives

The essence of decision analysis is to break down complicated decisions into small components that can be dealt with individually and then recombined logically. The process of breaking something down into its constituent parts refers to the process of developing an overall analytic structure. The formulation of the problem is *to identify what can be done and what might happen as a consequence*. In this process construction of a *decision table* or a *decision tree* is a very helpful method. Figure 1 shows a decision tree used to analyze the remediation strategies of contaminated forests. Decision tree compactly represents a set of scenarios. Any path from left to right through the tree constitutes a scenario. We will discuss in more detail these scenarios when discussing the strategies which can considered for cleaning up the contaminated forest.

One main stage in the decision analysis is to identify the alternative courses of action. In considering an intervention, all feasible actions should be defined - including no action. When defining an action, its feasibility should also be considered; could it be implemented in practice as it has been planned? For instance, it should be taken into account that society is not neutral to the choice of action. The remedial actions which were considered in this study are no action, control of wood material, control of access and removal of various parts of vegetation, i.e., trees, stumps, udervegetation and/or soil.

If in any of the defined areas (I, II or III in this analysis) no recovery operation, control of wood material or control of access is taken, the contamination is left in full in the forest. The amounts of radioactive materials will decrease with time through radioactive decay and by resuspension, which will cause transfer of radionuclides also to habilitated areas exposing unidentified people (projected release scenarios). The resuspension over 70 years is estimated to be 15%. Also, if the use of contaminated wood material is not restricted, its use will cause transfer of radionuclides to living environment. It is estimated, that the total amount of transfer in this pathway will be 30% over 70 years.

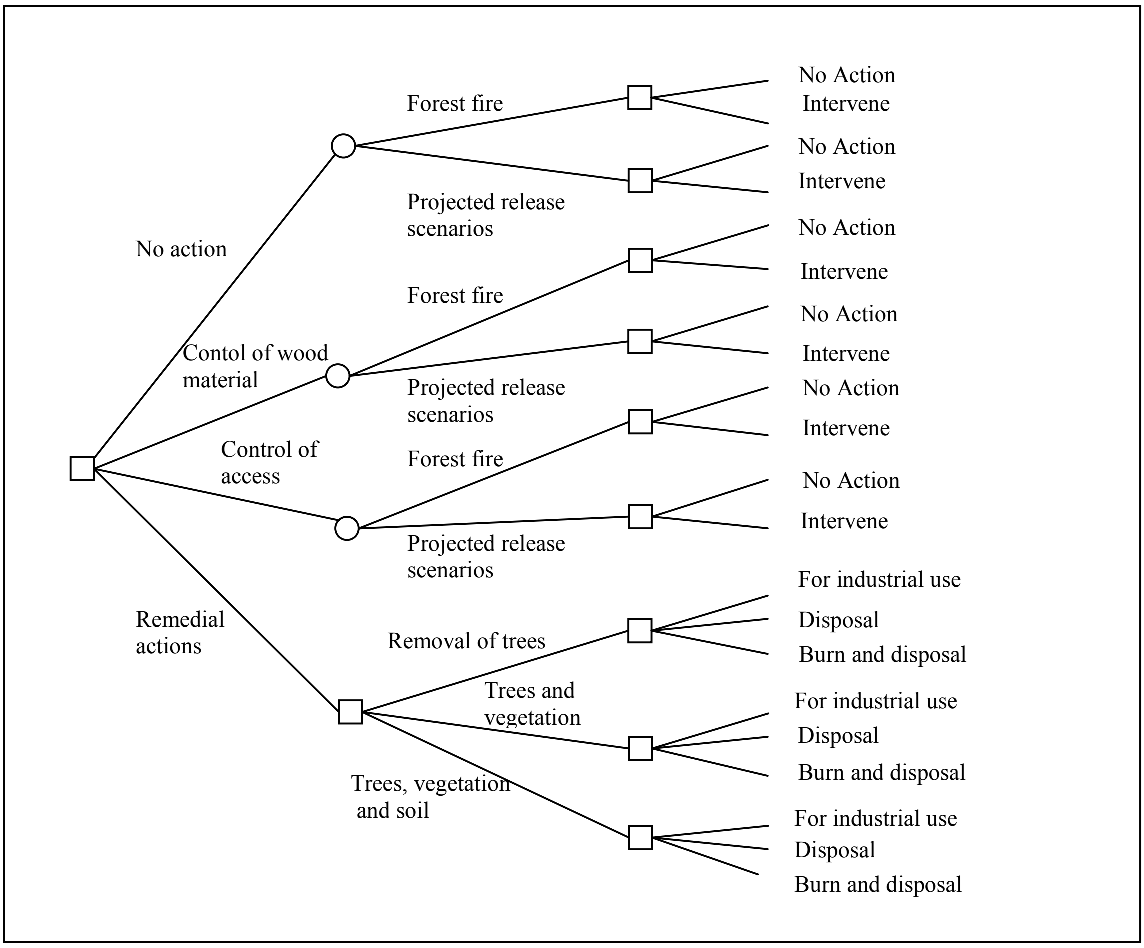


Figure 1. Decision tree to analyze the cleanup strategies of contaminated forest.

A forest fire will cause a spread of radionuclides. According to the statistics there are a few hundred forest fires in Finland every year in which 0.05 km^2 of forest is burnt on average. The probability, that a forest fire would occur in the contaminated area is less than 0.01 in a year. By assuming that 50% of radionuclides being in forest will be released in a fire, gives the result that the expected collective dose to the public would be very low (few ten's of mmanSv) as compared to the other pathways. Thus a forest fire is not an important scenario when considering the actions to be taken.

Decontamination of forest could be done by removing trees, stumps, undervegetation and/or soil. If all these are removed after two years it is estimated that 20% of radionuclides will remain in the contaminated area. When only trees and undervegetation are removed after two years the cleanup efficiency is estimated to be 60% in practice. During the first season the radionuclides are mostly in canopies, and by removing the trees the practical efficiency of decontamination is estimated to be 50%.

Based on the information mentioned above six strategies as defined in Table II were considered.

Table II. Strategies for recovery operations in forest areas defined in terms of their effects on the areas I, II and III.

Strategy	Removal of trees [a]	Removal of trees and underveg etation [b]	Removal of trees, underveg etation and soil [b]	Control of access [c]	Control of wood material	No action
1	II		I	I, II		III
2	II	I		I, II		III
3		I, II		I, II		III
4				I, II		III
5				I, II, III		
6			I	I, II	III	

a) Action is taken during the same season.
b) Action is taken two years after the fallout.
c) Projected period for control of access is 70 years.

Actually many more strategies could be considered by combining the areas and possible decontamination strategies. The limiting the analysis to those above would, however, not reduce the possibilities for evaluating the best course of action. Some strategies are not even feasible, e.g., it is not possible to remove the trees in area I during the same season, because the individual doses would be unacceptable high; the dose rate would be one mSv/h. Furthermore, as is indicated in the decision tree, there are three different methods to treat contaminated and removed trees:

1. Industrial use of trunks in sawmills or in pulp industry. Disposal of branches and barks as such or as ash after burning as fuel.
2. Chipping the trees, branches and stumps and burning the chip in power stations. Disposal of the remaining ash.
3. Disposal of trees as they are or in the chipped form.

These optional methods will be discussed below in more detail.

1. Industrial use. The method can not be easily applied. In principle, if trees are barked in the same or in the following season, the wood itself will be clean and the activity will be mostly still in the bark and in the branches. However, only big trees are barked in sawmills nowadays. There is a lack of machines suitable for this action to be done in the forest. Also, the distribution of contamination during the barking process would be unacceptable high.

If the trees are used in the chemical pulp industry, the pulp will be clean because during the process the radionuclides will be removed and they remain in the waste sludge. The contamination of machines would be a problem.

The most serious problem is the public opinion. Although it could be shown that the products made of contaminated material would be free from radioactivity, the industry and the population would in all probability not accept them. Public can be very suspicious about this kind of products as was demonstrated after the Chernobyl accident. Also, clean wood material would be available. Thus, the industrial use of contaminated trunks have to be rejected as a strategy.

2. Burning of wood before disposal. There are small (5 MW) and large (20 - 200 MW) power stations in every Nordic country, which are suitable for burning chipped wood material. If proper electrostatic precipitators are used, 95-99% of radionuclides will remain in the ash. The amount of waste ash to be disposed would be small. An ash contents of 5% have been used in the calculation. However, there will be some suspicion of burning radioactive material, especially among the population in the vicinity of the power stations.

3. Disposal of all material as such. Undervegetation, litter, humus and soil have to be disposed as such. Wood material can also be disposed as it is, but chipping the trees, branches and stumps, however, will help in the disposal and rotting of material. In all cases, final disposal cannot be undertaken before the organic material is rotten.

Burning of wood before disposal and disposal of all material as such are the two optional methods considered in the analysis.

8.4.2. Objectives and attributes

Having found the courses of action, the next main step is to identify all attributes (measures in figure 2) relevant to the decision. One technique to identify an operational set of attributes, is to start by listing all important objectives (goals in figure 2), such as minimizing health detriment, monetary cost and social disruption. In order to check the list, the objectives can be divided into general categories: health, safety, social, political, psychological and economical effects. Many of these objectives will necessarily be part of the decision making process following radiological emergencies. Some of the objectives might be directly measured on a numerical scale and some should be further divided into sub-objectives in order to be measurable. This kind of numeric variable is called an attribute. An attribute is used to measure the performance of actions in relation to an objective. Natural attributes are, e.g., immediate deaths, cancer cases or reduction of the lifespan. An *attribute hierarchy* (*value tree*) can be useful in defining attributes and objectives. Figure 2 shows the value tree for the remedial operations for the problem in hand.

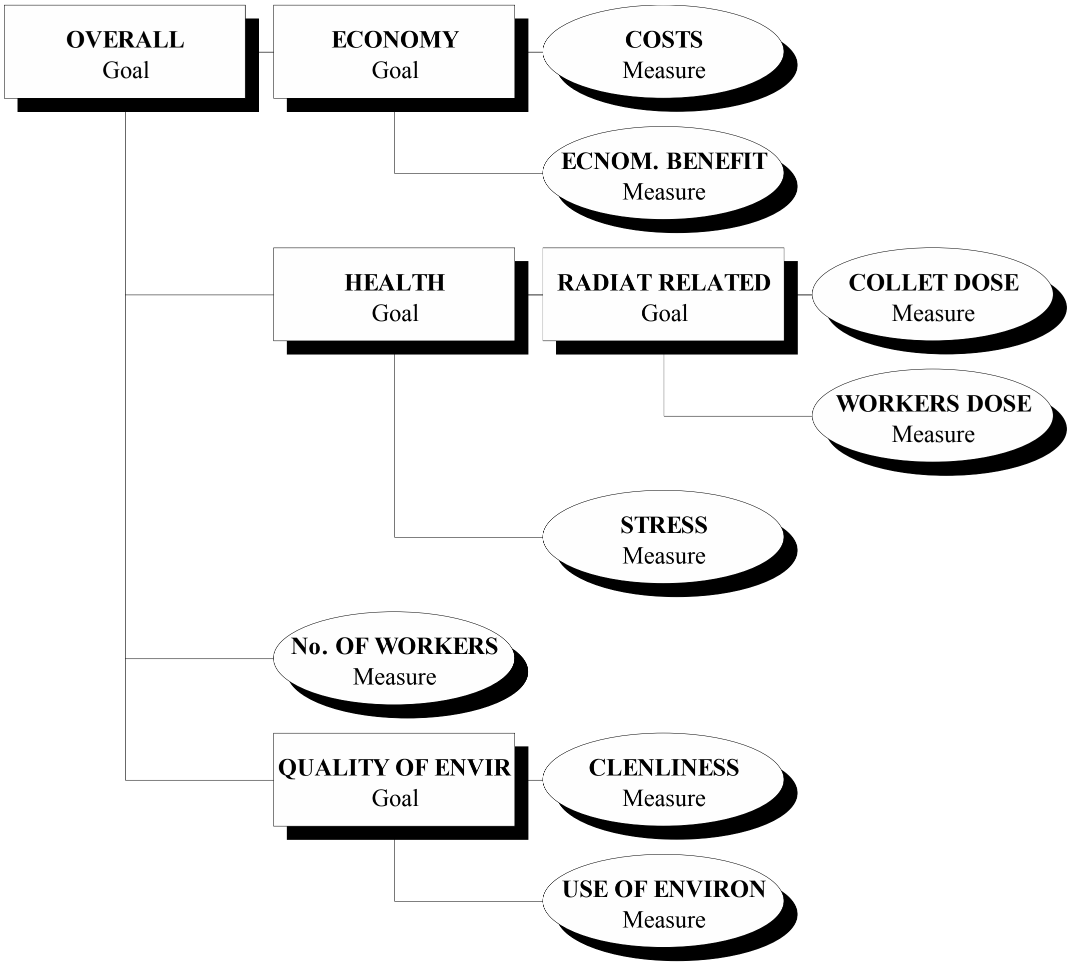


Figure 2. Hierarchy of attributes used in the decision model.

The attributes used in the analysis are defined as follows.

The effect on *health* is seen to have two components, of which radiation related health effects is further divided into two sub-attributes: these are doses to the workers and dose to the public.

Dose to the public. Because exposed individuals are not identifiable, the value of this attribute is assessed as the projected collective dose to the public (manSv). This relates to the expected number of fatal cancers caused by radiation, calculated by applying a risk factor of 5% to the dose in manSv.

Doses to the workers. Projected individual doses to the workers carrying out the recovery operations (mSv).

Number of workers carrying out the recovery operations. As initially planned the recovery operations will cause unacceptable high individual doses to the workers (several ten's of mSv). To keep the doses acceptable, i.e., below the dose limits, more workers should be employed. Thus, an objective will be to keep the number of workers as low as possible.

Stress. Psychological stress caused by radiation both to the public and workers. Stress will be decreased or increased by protective actions and it reduces the quality of life. This attribute aims to capture also the stress caused by unemployment of workers in the affected area and worry felt by land owners.

Quality of the environment. This attribute is seen to have two sub-attributes; *Cleanliness of the environments* and the *use of the environment* for refreshment. These attributes are aimed to capture the reduction in the quality of the contaminated areas and the living areas close to the contaminated forest, disposal site and around power stations burning radioactive wood.

Economic benefit. The monetary benefit to the industry and the society obtained by burning the wood as fuel (MFIM).

Costs. The monetary costs caused by implementing recovery operations. Total costs include direct costs of operations (harvesting, transportation, disposal), control of the area, loss of income and lost capital services (MFIM).

8.4.3. How the strategies perform on each attribute

Now the consequences of the actions can be assessed, i.e., how well the different actions perform for each of the lowest level attributes in the value tree. The consequences are the values of attributes in various actions, e.g., the assessed dose if action is taken and the action's monetary costs. The measurement of these two attributes is easy, because we can identify the variables representing them. However, for attributes, such as stress and quality of environment, it is more difficult to find a proxy attributes or variables that can be quantified. The techniques, which can be used to express the preferences over the values of an attribute, are *direct rating* and the use of *value functions*.

Direct rating can be used with attributes which cannot be represented by easily quantifiable variables. In this technique, the most preferred option for, e.g., stress, a value of 100 is given and the value of zero for the least preferred option. The other options are ranked between zero and 100, according to the strength of preference for one option over another in terms of stress. Although this technique seems to be robust it should be emphasized that there are methods to check the consistency of the elicited numbers. Also, numbers do not need to be precise. As will be pointed out later when discussing sensitivity analysis, the choice of an action is generally fairly robust, and often substantial changes in the figures are required before another option is preferred.

The preferences over values of an attribute can be changed numerical also by a value function. As in direct rating the most preferred option for an attribute, a value of 100 (or 1.0), is given, and the value of zero for the least preferred option. There are several methods which can be used to elicit the intermediate values to form a continuous value function. The simplest conversion, which is used in this analysis, is a straight line, where a unit change in the preference of an attribute corresponds to an equal change in value.

The assessed values of attributes for each action are given in Table III.

Table III. Values of the attributes for strategies defined in Table II.

Strategy	Collective dose to public (manSv)	Individual dose to workers (mSv)	Number of workers	Economical benefit (MFIM)	Costs of action (MFIM)
1a	5460	20	1270	120	121
1b	5380	20	1220	0	129
2a	5480	20	1230	120	119
2b	5400	20	1180	0	127
3a	5390	20	3550	166	151
3b	5370	20	3570	0	163
4	5560	0	0	0	66
5	2050	0	0	0	4710
6b	3140	20	170	0	3200

a) Wood material is burned as fuel before disposal
b) All material is disposed as such.

In assessing the collective dose to the public the external dose and intake of radionuclides in all relevant pathways were considered, i.e., the dose caused by resuspension, burning radioactive wood, using contaminated wood material and forest fire. Of these the use of contaminated wood would cause the highest doses, 3500 manSv. The inhalation dose over 70 years was considered to be small compared to intake and external dose. There are no models designed specifically for this kind of problem. Therefore, the dose calculations have to be based on expert judgments and as far as possible on the dispersion and dose prediction models developed primarily for accidents at nuclear power plant. The dose predictions were done by ARANO software package (Sa77).

The dose to each worker group in each work phase were calculated separately; felling the trees, removal of undervegetation and soil, transportation of trunks, chip and ash, and disposal of wood material or ash. The software package MATERIA was used to assess the individual doses to workers (Ma93). In most cases the estimated doses were unacceptable high, several ten's of mSv, and in these cases the number of workers was increased to keep the individual doses below 20 mSv.

The use of wood will strongly be affected by public opinion if the action to control of wood material would is taken (strategy 6b). Because the contaminated area would be commonly known, all the wood material from these areas would not be accepted by the industry. This will cause a reduction in collective dose, but at the same time will increase the monetary losses to land owners. It was estimated, that one third of wood otherwise used, i.e., if no action is taken, will be rejected.

The monetary costs of actions and also benefits were calculated using the information collected in other study of this project (cf. chapter 6), Finnish statistics and similar monetary costs assessment methods as is presented in COCO-1 report (Ha91). The costs of lost capital service and removal of trees are the main costs components.

The scales for stress and quality of the environment attributes were developed judgmentally and the values are given below in Tables IV and V. Higher score represents a more preferred actions.

Table IV. Scores of stress attribute.

Strategy	1a	1b	2a	2b	3a	3b	4	5	6b
Score	80	90	90	100	60	70	40	0	50

a) Wood material is burned as fuel before disposal
b) All material is disposed as such.

Strategy 2b was given the highest score because it treats the workers, the population and land owners fairly, offering a certain degree of decontamination and because the wood would not be burned there would be no local fallout. Also, the amount of disposed waste would be acceptable. It was felt that to reduce psychological effects it is important to take the actions shortly after the accident and at the same time to avoid too excessive actions. Strategy 5 was given the lowest score. It treats area III differently than others by offering reassurance only by controlling the access to the area, but on the other hand, it would cause lot of problems to individual land owners even if the cost of action would have to be borne by the society. Strategy 4 was seen as next least acceptable. It offers no reassurance of decontamination, although there would be no doses to the workers. The scores for other strategies were assessed according their strength of preferences using similar arguments.

Table V. Scores of quality of the environment attribute.

Strategy	1a	1b	2a	2b	3a	3b	4	5	6b
Score	100	90	80	70	90	80	20	0	50

a) Wood material is burned as fuel before disposal
b) All material is disposed as such.

Although there are sub-attributes, the cleanliness and the use of environment, below the quality of environment attribute it was thought to be appropriate to assess the scores directly to the higher level attribute, i.e., to the quality. Strategies 4 and 5 were given the worst scores because the contamination would be left untouched in the environment. The objective, the use of the environment was also in its worst position in strategy 5. The control of access (with fences) would also impair the quality of the environment. Although there would be a small release of radionuclides into the environment in strategy 1a when burning contaminated wood, it was felt that this strategy offers the best quality of the environment. The other strategies were felt to be less attractive and the assessed scores are seen in the Table V.

In the analysis the figures given above, e.g., collective doses, were transformed linearly to 0 - 1 scales and their different relative lengths are taken into account in assessing the weights on attributes (see below).

8.4.4 Trade-offs

Before we can combine the values for different attributes in order to obtain a view of overall benefits which each action has to offer, we have to assess the weights on attributes. They represent the judgment of the decision maker on the relative importance of the levels of attributes. For example, how much he/she is ready to accept doses to individual workers to avoid a certain dose to the population. When assessing a trade-off value, it should be noticed that the importance of an attribute is not only dependent on its conceptual value, such as health, but also on its *range of values*, such as the number of cancer cases. The range means the difference in values in various actions, e.g., the difference in dose when the action is taken or not taken.

Swing weighting is applied in the analysis as an assessment method for scaling constants, i.e., the trade-offs. In the method a decision maker is asked to compare a set of pairs of hypothetical actions which differ only in their values along two attribute scales until an indifferent pair of options is found. For example:

Option A: The individual dose is 20 mSv and the collective dose is 0 mmanSv.
Option B: The individual dose is 0 mSv and the collective dose is 100 mmanSv.

If the options A and B are felt to be indifferent, it can be seen that it is more preferred to avoid higher individual risks than individually low but collectively higher risk. It is estimated, that the individual doses to the population are far less than one mSv on average. If we set the weight of the collective dose to one, and taking into account the 'length' of collective dose scale, 3510 manSv, and individual dose scale, 20 mSv, this suggests a weight (5*0.001*20/3510) = 0.00003 for the individual dose scale relative to the collective dose scale.

The weights were set on other attributes using similar judgments. For example, the following indifferent (marked with ~) pair of options was elicited for the number of workers and individual dose:

(1 men; 20 mSv) ~ (100 men; 1 mSv).

This assessment together with the fact that the number of workers scale has a length of 3570 men and the worker dose scale 20 mSv, means that number of workers scale is felt 36 times as important as the individual worker dose scale of 20 mSv. Altogether six trade-offs have to be assessed in order to have a complete set of weights. The following pairs of attributes were used to assess the weights, and the indifferent options are given below:

Collective dose/costs attributes:

(2 manSv; 0 MFIM) ~ (1 manSv; 0.25 MFIM)

Costs of action/monetary benefit attributes:
(0 MFIM; 170 MFIM) ~ (170 MFIM; 0 MFIM)

Collective dose/stress attributes:
(3000 manSv; 100 Stress) ~ (2000 manSv; 0 Stress)

Stress/quality attributes:
(50 Stress; 100 Quality) ~ (100 Stress; 0 Quality).

Based on these assessments the following weights are obtained (Table VI). *Note:* The weights are normalized so that the sum of weights is one.

Table VI. Weights of attributes.

Attribute	Weight
Collective dose	0.15
Individual dose of workers	0.000004
Number of workers	0.0002
Monetary costs of action	0.76
Economic benefit	0.03
Stress	0.04
Quality of the environment	0.02

8.5. ANALYSIS OF THE MODEL

At this stage we are in position to aggregate the values to find out how well each strategy performs overall. The *Additive model* was applied simply to add together an action's weighted value scores (weighted attribute values on each action) to obtain the overall benefit:

$$v(a) = \sum_i k_i v_i(a_i),$$

where $v_i(a_i)$ are single-attribute value functions, a_i are assessed values of attributes and k_i are weighting factors. *Note:* A sufficient condition for an additive decomposition of multi-attribute value function is mutual preferential independence of the attributes. An attribute X is preferentially independent of attribute Y, if the two preference values of attribute X do not depend on the value of Y. The existence of preferential independence is normally verified during the analysis - and should, in principle, be verified. If the conditions for an additive function exist, the weights are assessed by making trade-offs between attributes as described earlier.

To make the calculations slightly easier the decision model was build using the software package LDW (Sm93). The overall scores and ranking of strategies are as is given in table VII. Strategy 1a, decontamination in areas I and II, and no restriction in area III, is just optimal. In fact, strategies 1-4 rank very close to each other. This is due to area III, which because its large area has a strong effect on attribute values. In strategies 1-4 the same action is taken in the area III.

Table VII. Overall scores for the initial analysis.

Strategy	1a	1b	2a	2b	3a	3b	4	5	6b
Overall score	0.834	0.819	0.833	0.819	0.829	0.805	0.790	0.195	0.41
Rank	1st	4th	2nd	4th	3rd	5th	6th	8th	7th

It is wise to be skeptical about the ranking of the actions, if the variation of figures used in the analysis is not analyzed with a sensitivity analysis. We have to examine how robust the choice of an alternative is to changes in the figures. In many cases sensitivity analysis also shows that the data do not need to be accurate. Large changes in these figures are often required before one action becomes more attractive than another. If this is the case, then it would be waste of effort and time to elicit the numbers accurately.

There are several techniques presented in the literature to perform a sensitivity analysis. The most straightforward analysis applied here examines the effects of varying one parameter at a time. Although the method is simple it clearly indicates which factors are important and require refined assessment.

There are lot of uncertainties in the assessment of the collective dose and monetary costs. The weights of these attributes are also high. The sensitivity analysis on the weight of costs is shown in figure 3.

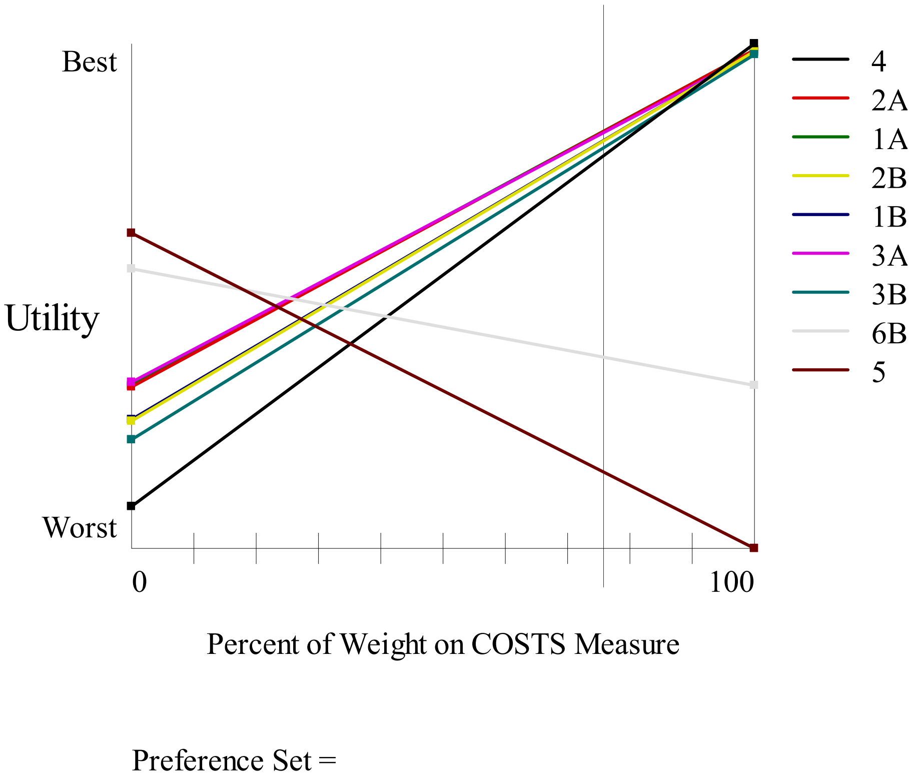
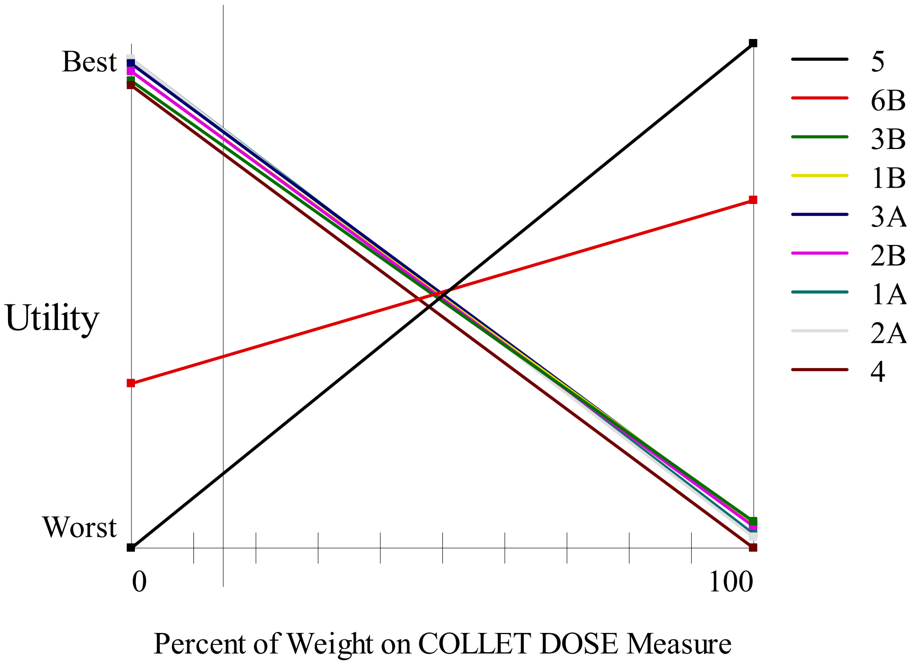


Figure 3. Sensitivity analysis on costs.

The weight on costs is about 76% of the total weight in the model and this value is marked with the vertical line in the figure 3. The overall score for each strategy against the percentage of total weight on costs are plotted with solid lines. The line with the highest intersection with the vertical line shows the optimal strategy, i.e., strategy 1a.

As the weight on costs is between 35% and 95% strategy 1a is just optimal, but below 35% strategy 6b and then strategy 5, and above 95% strategy 4 will be the best courses of action, respectively. Besides this range gives the accuracy needed in the weighting the costs attribute, it also reflects the required accuracy in the costs calculation because the 'length' of an attribute is taken into account when assessing trade-offs, on the assumption that there is consistency in costs calculation between strategies.

The sensitivity analysis on the weight of collective dose is shown in figure 4. With the present weight (15%) on dose, the strategy 1a ranks best. The highest value of the collective dose was obtained in the pathway where the contaminated wood is used without restrictions. It was felt that this might be too high. The analysis suggests that substantial changes would be required before the strategies 5 and 6 become more preferred.



Preference Set =

Figure 4. The sensitivity analysis on collective dose.

Because strategies 5 and 6 seem not to be the best course of action the analysis was revised omitting these strategies from the analysis. Doing this the effect of decontamination on decision is more clearly seen. The same trade-offs is used as earlier, but because the 'length' of scales are changed the following weights given in Table VIII are obtained:

Table VIII. Weights of attributes in revised analysis.

Attribute	Weight
Collective dose	0.086
Individual dose of workers	0.00003
Number of workers	0.0014
Monetary costs of action	0.16
Economic benefit	0.23
Stress	0.34
Quality of the environment	0.17

The ranking of strategies for analysis based upon above-mentioned weights are given in Table IX.

Table IX. Overall scores for the revised analysis.

Strategy	1a	1b	2a	2b	3a	3b	4
Overall score	0.73	0.60	0.72	0.59	0.69	0.47	0.33
Rank	1st	4th	2nd	5th	3rd	6th	7th

The ranking of strategies is - as it should be - the same as in the initial analysis. However, the difference between the strategies is more clearly seen. Now the sensitivity analysis on the weight of collective dose is as is shown in figure 5.

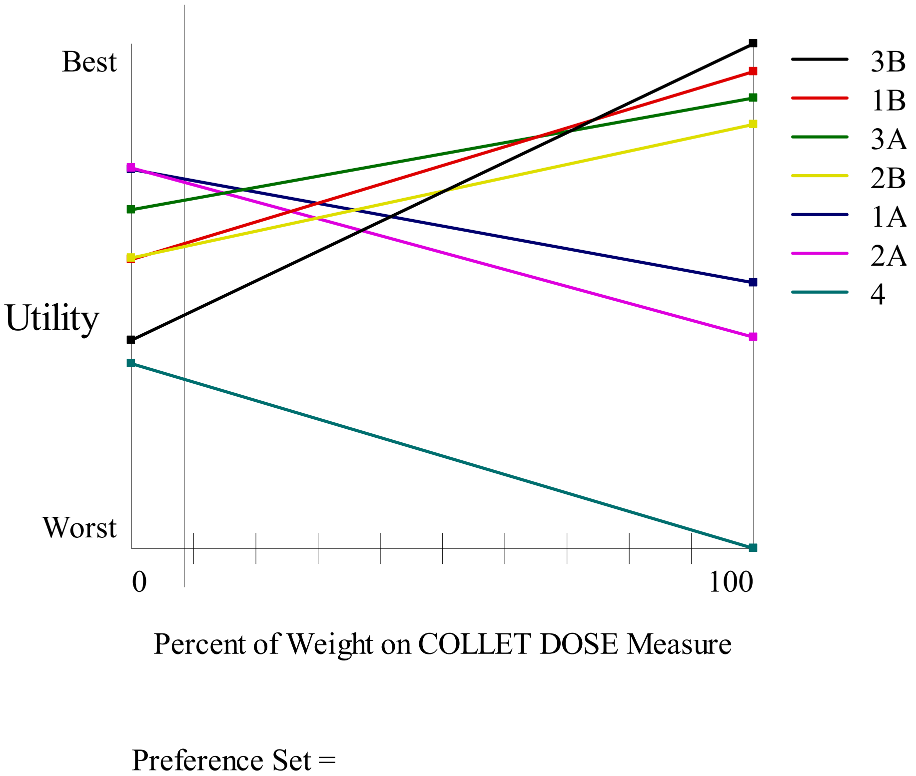


Figure 5. Sensitivity analysis on collective dose. Strategies 5 and 6 are omitted from the analysis.

The difference between stetegies 1a, 2a and 3a is not large and the analysis suggests that the best course of action could be found in this group of strategies. There should be modifications in strategies 1b, 2b and 3b, or changes in numbers or trade-offs before this group of action will become more attractive. As is shown in figure 5 strategies 2b and 4 are never optimal actions considering the values and the trade-offs used in the analysis.

Before final conclusion on the action it is useful to gain further understanding considering stress attribute. It was unpleasant to assess numbers on this attribute and because the weight on this attribute is also high, its effect on decision should be further considered. This could be done with figure 6.

Figure 6 shows that increasing scores go with increasing preferences. The figure plots the overall utility for all other effects excluding stress against stress. In principle the strategy represented by a cross in the upper right corner is most preferred. On the upper right boundary (Pareto or efficient frontier) lie strategies 1a, 2a, 3a and 2b in this diagram. The optimal choice depends on value put on stress. As the value increases from 0 to 100 the optimality moves from strategy 3a to strategy 1a and through 2a to 2b. These strategies offer better choice, i.e., they dominate strategies 1b, 3b and 4 which can never be optimal without changes in their scores and weights.

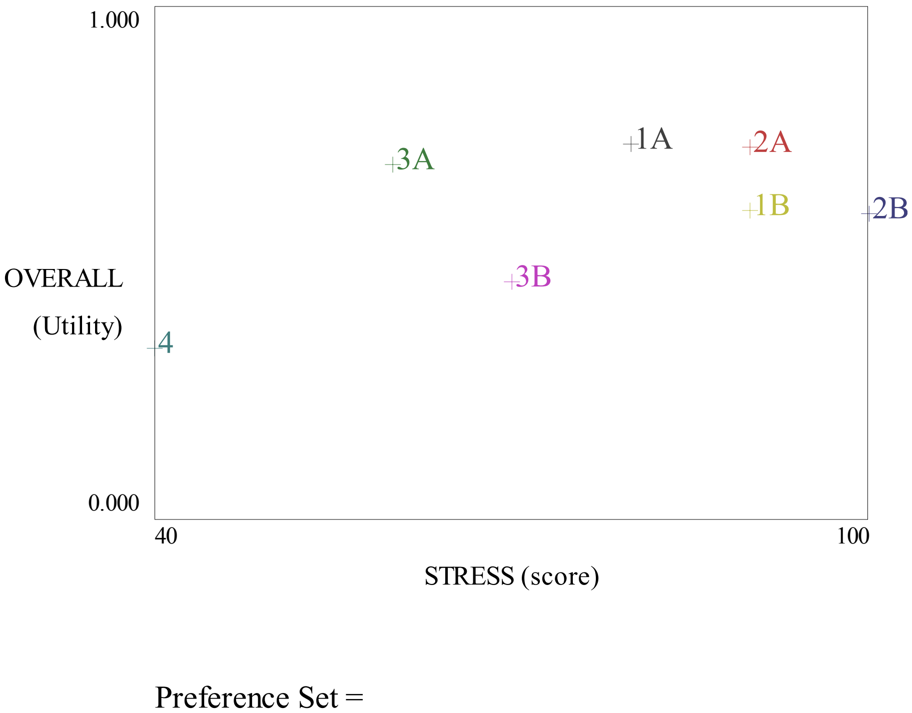


Figure 6. Plot of utility against stress.

8.6. CONCLUSIONS

The objective of this study has been to give an illustration of decision analysis and the application of the analysis when planning countermeasures for forest areas in order to mitigate the consequences of a nuclear accident. The basic principles of radiation protection are based on the justification and optimization of protective actions. Decision analysis, although closely entwined with these principles, does not interpret the results with this terminology. The aim of decision analysis is to find the best solution to a problem based on the rationality of the decision maker(s). However, the result of decision analysis can be translated to correspond to the basic principles of radiation protection.

At the beginning of a decision analysis all feasible protective actions are defined, including the action of doing nothing. When assessing the justification of protective actions, the present situation forms the basis to which the actions are compared, with respect to the preferences of society represented by a decision maker. The preferences and trade-offs - the judgmental inputs to analysis - form the basis for justification. A protective action is justified if the values connected to it are greater than those of no action.

The optimization of the intervention is achieved by ranking all feasible actions. The action with the highest ranking will produce the maximum benefit. In optimization it is thus assumed that all actions and attributes are defined at the beginning of an analysis. In practice, however, it is not possible to define all actions before making some preliminary numerical assessments and running through some rough calculations to gain a feeling for what numbers are important and require refined assessment. The optimization of intervention means this iterative process of maximization of protection in all its essentials. The setting of an intervention level in an accident situation or in planning of the intervention levels is seldom a purely mathematical problem.

The decision analysis performed suggest that a strategy somewhere between 1a and 2a would be the best course of action to be taken in the given situation. There would be a few differences between these strategies. The treatment of areas are quite the same: in area II trees would be removed during the same season and in area III 'doing nothing' would be taken in both strategies. No action in area III was deemed to be more preferred to the actions 'control of access' or 'control of wood material'. In the area I the trees and undervegetation are removed and the only difference between strategies 1 and 2 is the removal of soil in strategy 1. Also, strategy 3a could be considered as an action. In all strategies the removed trees would be burned as fuel.

There are different preferences connected to the values of attributes. Therefore, *the values of attributes and trade-offs are subjective*, not objective. Expressing the value may be both unpleasant and difficult, but often it is very crucial when assessing an intervention level. Since the values are subjective, no universal values exist. The values are related to the unique problem, and in addition, they change according to opinions and resources. In addition, people have strong feelings and beliefs about these values, which typically are not numerically quantified and do not exist in monetary form. Careful structuring of the problem is necessary to identify the underlying multidimensional values, attitudes to risk and trade-offs related to the problem. To create more insight more research is needed, specially on the less quantifiable factors.

The analysis represented above is based on hypothetical accident. In real problem depending on prevailing situation where the fallout area could be located in the map, more strategies would have to be considered. Also, the factors entering the decision are dependent on situation. Thus, the results of the performed analysis could not be applied in real situation as such, but the actions and factors should be revised and the calculations redone. The strategies found appropriate in the analyzed situation might turn out not to be the most preferred in the real problem, however, they might well indicate the course of actions to be considered.

8.7 REFERENCES

Fr88 French S. Decision theory: an introduction to the mathematics of rationality. Ellis Horwood, Chichester, 1988.

Go 92 Goodwin P. and Wright G. Decision analysis for management judgement. John Wiley & Sons, Chichester, 1992.

Ha91 Haywood S., Robinson C. and Heady C. COCO-1: model for assessing the cost of offsite consequences of accidental releases of radioactivity. NRPB-R243, Chilton 1991.

IAEA91 International Atomic Energy Agency. Radiological protection principles for sources not under control: their application to accidents. Safety Series No. 109, IAEA, Vienna 1991 (in press).

ICRP91 International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. Publication 60, Pergamon Press, Oxford, New York, Frankfurt, Seoul, Sydney, Tokio 1991.

ICRP89 Optimization and decision-making in radiological protection. ICRP publication 55. Annals of the ICRP 20(1), 1989.

Ke76 Keeney R. and Raiffa H. Decisions with objectives: preferences and value tradeoffs. John Wiley & Sons, New York, 1976.

Ke77 Keeney R. The art of assessing multiattribute utility functions. Organizational Behaviour and Human Performance 19, pp. 267 - 310, 1977.

Ma93 Markkanen M. Personal communication. Finish Centre for Radiation and Nuclear Safety.

Sa77 Savolainen I and Vuori S. Assessments of risks of accidents and normal operation at nuclear power plants. Technical Research Centre of Finland, Nuclear Engineering Laboratory, Electrical and Nuclear Technology Publication 21. 1977.

Si91 Sinkko K. Decision analysis and rational countermeasures in radiation protection. Finnish Centre for Radiation and Nuclear Safety, STUK-B-VALO 70. Helsinki 1991.

Sm93 Smith G. Logical Decision: multi-measure decision analysis software. Logical Decisions, 1014 Wood Lily Drive, Golden, Colorado 80401, USA.

Wi86 Von Winterfeldt D. and Edwards W. Decision analysis and behavioral research. Cambridge University Press, 1986.

ACKNOWLEGEMENT

We would like to thank Dr. Jukka Lehto for his participation in the analysis, and for his advice and comments on the draft manuscript.