Multi-criteria Decision Support and Evaluation of Strategies for Nuclear Remediation Management

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Abstract

Environmental emergency situations can differ in many ways, for instance according to their causes and the dimension of their impacts. Yet, they share the characteristic of sudden onset and the necessity for a coherent and effective emergency management. In this paper we consider decision support in the event of a nuclear or radiological accident in Europe. RODOS, an acronym for Real-time On-line Decision Support System, is a decision support system designed to provide support from the early phases through to the medium and long-term phases. We describe the role of multi-criteria decision analysis (MCDA) within RODOS in ensuring the transparency of decision processes within emergency and remediation management. Special emphasis is placed on the evaluation of alternative remediation or countermeasure strategies using the multi-criteria decision support tool Web-HIPRE in scenario focused decision making workshops involving different stakeholder and expert groups. An explanation module, which generates natural language explanations to enhance the understanding of the evaluation process, therefore contributing to the direct involvement of the decision makers, is integrated into Web-HIPRE with the aim of increasing their confidence in the results of the analyses carried out, forming an audit trail for the decision making process and improving the acceptability of the system as a whole.

Keywords: Decision Support Systems, Emergency Management, Remediation, Multi-criteria Evaluation, Sensitivity Analysis, Stakeholder Involvement, Natural Language Generation

1 Introduction

Emergency situations, both man-made and natural, necessitate a coherent and effective emergency management involving complex decisions. Many conflicting objectives must be resolved and priorities must be set while the various perspectives of many stakeholder groups must be brought into some form of consensus. In order to ensure transparency during the decision making process multi-criteria decision analysis is vitally important [1,2,3,4]. In particular, the evaluation of long-term remediation strategies after a nuclear or radiological accident can benefit from operationally applicable multi-criteria methods and evaluation techniques to guide and support the decision makers during the decision making process.

Nuclear emergency management is different to emergency preparedness and management which often involve contingency plans or checklists that have been prepared in advance and are more or less regularly utilized in emergency exercises. On the one hand, nuclear emergencies and their resulting far-reaching consequences are more complex. On the other hand, they are less known due to their fortunately low frequency of occurrence. Devising a contingency plan for nuclear emergencies that covers all imaginable eventualities is an impossible task, which highlights the need for a flexible system providing guidance and support for the team faced with the difficult job of managing a nuclear emergency.

In this paper the focus is on decision problems in the context of environmental remediation management after a nuclear or radiological accident in Europe. In the early phase emergency management involves urgent decisions on short-term measures such as evacuation, sheltering or distribution of stable iodine. In the longer term, more complex decisions on remediation strategies and agricultural countermeasures are required. A characterization of the different phases of emergency and remediation management and corresponding (counter)measures is shown in Figure 1.

Figure 1: Implementation of decision support throughout all phases of emergency management

The many questions which arise from the requests of an emergency management team need to be dealt with. One system that offers comprehensive support in managing nuclear or radiological incidents is the real-time on-line decision support system RODOS. In order to focus on the needs of the decision making process, the evaluation tool Web-HIPRE, a Java-based software for decision analytic problem structuring, multi-criteria evaluation and prioritization [5,6,7], was recently integrated into RODOS providing support in transparently and coherently evaluating the overall efficacy of possible countermeasure and remediation strategies [2,8]. Furthermore, an ”Explanation Module” [9,10], which offers the possibility to generate natural language reports that explain the results of the decision analysis and moreover form an audit trail, has been implemented into Web-HIPRE. The new evaluation tool in RODOS has been tested in a series of workshops across Europe to demonstrate its capabilities and to gather feedback whether or not such a tool could be applied in the decision making process in nuclear emergencies. Another aim of the workshops was the identification of (technically and socially) feasible countermeasure and remediation strategies and relevant decision criteria. In Germany, two workshops were organized in collaboration with the Federal Office for Radiation Protection (BfS) in Freiburg, Germany.

Bringing together various fields of expertise and different perspectives, the described interdisciplinary methods are also very relevant for researchers and practitioners in engineering since it is universally applicable. On the one hand, it is easily extendable to industrial emergencies where both, an increased awareness of the possibility of technical failure of industrial systems and an improved preparedness to cope with emergencies, are desirable. On the other hand, it can in general be used to support a structured resolution of any complex decision situation.

This paper is structured as follows: section 2 introduces the basic structure, components and features of the RODOS system. Section 3 gives an overview on Multi-Attribute Value Theory (MAVT), as one field of research within MCDA, and the evaluation tool Web-HIPRE. Subsequently, section 4 describes the integration of the Explanation Module into Web-HIPRE. Section 5 deals with the combination of MCDA and moderation techniques in a workshop, aiming at allowing for the consideration of the results of various engineering disciplines. One of the German decision making workshops, the hypothetical case study upon which it was based, the course of action and selected results are described in section 6. Finally, section 7 summarizes the main results and indicates future research needs in this area.

2 The Real-time Online Decision Support System RODOS

The RODOS system is designed to provide consistent and comprehensive information in the event of a nuclear or radiological accident in Europe (see: www.rodos.fzk.de). After the nuclear accident from Chernobyl in 1986, the development of RODOS became one of the major items in the area of radiation protection of the European Commission's Framework Programs [11,12,13,14].

The support provided by RODOS ranges from largely descriptive reports, such as maps of the predicted, possible and, later, actual contamination patterns and dose distributions, to a detailed evaluation of the benefits and disadvantages of various countermeasure strategies and their ranking according to the societal preferences as perceived by the decision makers [11,12,14]. Models and databases within RODOS contain extensive information about site and plant characteristics of the different nuclear power stations in Europe and the geographical, climatic and environmental variations. Its operational application requires on-line coupling to radiological and meteorological real-time measurements and meteorological forecasts from national weather services. The RODOS system is characterized by its conceptual architecture which consists of the following three subsystems [13]:

- Analyzing Subsystem (ASY) modules process incoming data and forecast the location and quantity of contamination including temporal variation.
- Countermeasure Subsystem (CSY) modules simulate potential countermeasures, check them for feasibility, and calculate their expected benefit in terms of a number of attributes.
- Web-HIPRE constitutes the Evaluation Subsystem (ESY) allowing to rank countermeasure strategies according to their potential benefits or drawbacks and preference weights provided by the decision makers.

RODOS offers decision support from the early phase through to medium-term and long-term countermeasures implemented weeks, months or years after an accident. In the early phase, emergency management involves decisions on emergency actions, such as evacuation, sheltering or distribution of stable iodine (cf. Figure 1), which are usually limited to areas within a few tens of kilometers of the nuclear accident. Since decisions on whether or not to implement such countermeasures depend to a great extent on the spread of the (radioactive) plume and the estimated contamination levels, emergency management in the early phase is closely related to the predictions of the ASY. In the longer term, more complex decisions on decontamination and remediation strategies, restricted access measures (e.g. relocation) and agricultural countermeasures are required (cf. Figure 1). Thus, emergency management in the later phases is rather connected to the calculations of the CSY and ESY where the ESY seeks to provide transparency and coherence in the evaluation of alternative countermeasure and remediation strategies, whose potential benefits and drawbacks are quantified by the CSY [15].

The prediction of the radioactive dispersion through the various pathways and thus the prediction of the radiation exposure of the population during and after a nuclear event is a very important part of a system such as RODOS. Detailed information as regards this subject can for instance be found in [16,17,18]. However, in this paper, we focus on the ESY and thus the use of MCDA in nuclear emergency management.

3 Multi-Attribute Value Theory (MAVT) and Web-HIPRE

The MCDA methodology used in the evaluation module is based on decision analysis. It is a field of research which is concerned with the structured evaluation and support of decision problems with multiple criteria and uncertainty [19]. Problems with successive decision and uncertainty nodes are modeled with decision trees and influence diagrams. The terminology can easily be confusing as a decision tree refers to a different model than the attribute tree model used here. The multi-criteria evaluation of alternatives under uncertainty is dealt with in multi-attribute utility theory (MAUT) where uncertainties are modeled probabilistically. In our case we use multi-attribute value theory (MAVT), where uncertainties are not considered explicitly. The theory develops methods to structure and analyze decision problems by means of attribute trees and to elicit the relative importance of criteria in this setting. In an attribute tree the overall goal or objective is divided hierarchically into lower level objectives (also called criteria) and measurable attributes (also called lowest level criteria). A decision alternative x is evaluated on each attribute, i, by means of a value function $v_i(x)$. Under the assumption of mutual preferential independence of attributes we can use the standard additive aggregation rule [20]. Then the overall value of an alternative x is evaluated as

$$v(x) = \sum_{i=1}^{n} w_i v_i(x),$$

where n is the number of attributes, w_i is the weight of attribute i , and $v_i(x)$ is the rating of an alternative x with respect to attribute i. The sum of the weights is normalized to one, and the component value functions $v_i(\cdot)$ have values between 0 and 1. The weights w_i indicate the relative importance of attribute i changing from its worst level to its best level, compared with the changes in the other attributes.

Weights can be elicited by different weighting procedures. The simplest way is to give them directly by point allocation. Web-HIPRE supports all the common weighting methods based on relative comparisons. In the SWING procedure (see [21]), 100 points are first given to the most important attribute. Then, less points are given to the other attributes depending on the relative importance of their ranges. The SMART method (see [21,22]) is similar, but the procedure starts from the least important attribute keeping it as the reference. In SMARTER (see [23,24]), the weights are elicited directly from the ranking of the alternatives. The Analytic Hierarchy Process (AHP) [25] is a decision modeling approach developed in parallel with the attribute tree MAVT method. The AHP has a fixed comparison procedure based on a nine-point-scale which includes redundancy and thus allows the estimation of the consistency of the statements, too. When the questions in the weight elicitation refer to value differences then the results from an AHP procedure can be shown to correspond with those of MAVT analysis [26]. Thus one can consider AHP as one MAVT method in the MCDA approach. For comparison and details of the use of different methods see [27] and [28]. Web-HIPRE allows one to use any combinations of these weighting methods in one model. There are also a number of techniques for the specification of the value functions. However, in many cases the assumption of linear value functions is justified if the set of outcomes of the alternatives are not very far apart.

The essential interactive steps in a MAVT analysis include first the structuring of the problem into a hierarchy of criteria and second the elicitation of the relative importance of the criteria. The importance of the criteria reflects the ranges of the attributes in a particular evaluation as well as the trade-offs between attribute values. An attribute tree allows to represent and evaluate the decision makers' priorities by an overall value score and break it down under different criteria as well as to study the sensitivity to changes in the weights. These stages are easy to perform with the support of Web-HIPRE. The structuring can be done interactively and the criteria and alternatives can be directly linked to explanation web pages to help the decision maker learn more details about them. The user interface of Web-HIPRE is seen in Figure 7 - Figure 9 (section 6). In an evaluation workshop Web-HIPRE can be run over the internet or local intranet so that the participants can also work independently with their own models. These can be easily evaluated together or even combined into a joint group model. The use of Web-HIPRE is described in [7] and [29].

4 Explanation Module

After ranking alternative strategies, Web-HIPRE illustrates the results of the ranking process as well as a sensitivity analysis graph. Users can view the evaluation results and choose a strategy. They can also read explanation reports that justify the ranking of alternatives.

Explanation facilities contribute to positive user attitudes and improve user performance [30]. They have proven to be useful to users, experienced professionals as well as novices [31]. They influence user perceptions such as trust, confidence and satisfaction and increase levels of acceptance and learning [32].

An Explanation Module has been developed to justify the advice of the ESY, the evaluation subsystem of RODOS, and to increase the trust and confidence of the DMs in the results of the whole system [9]. In practice, the executive DMs usually do not operate the system themselves but by generating an audit trail the Explanation Module seeks to help the emergency management team, advising the DMs, in communicating the results in an understandable way. The Explanation Module adds transparency to the ranking process, by generating two natural language reports:

- A "Comparative Report" that interprets the evaluation results and compares two strategies. The report discusses how well a strategy rates over the evaluation criteria, outlines arguments for and against each strategy, examines how much better a strategy is over another and highlights factors that differentiate between two strategies.

- A "Sensitivity Analysis Report" that interprets sensitivity analysis graphs, illustrates the effect of changing the weight of an attribute in the ranking of alternative strategies and discusses the robustness of the most preferred strategies.

Figure 2: The general structure of the Explanation Module

Figure 2 illustrates the structure of the Explanation Module. The input of the module comprises qualitative data in the form of an attribute tree and quantitative data in the form of a decision table that contains the values of decision parameters such as scores and weights. The Explanation Module then applies natural language techniques [33] and statistical methods [34] to generate understandable reports in English. A description of a user session with the Explanation Module follows.

The user interacts with the interface of Web-HIPRE and submits a command which is then translated into a communicative goal such as "compare strategy disposal with strategy storage relative to criterion radiological effectiveness" and "interpret the results of a sensitivity analysis on the weight of resources". The Explanation Module processes the goal and initiates the natural language generation process which involves three stages (a message is defined as a collection of data that convey a linguistic concept):

- Content determination which involves determining the content of the report i.e. what messages to communicate to the users.

- Discourse planning which involves establishing the structure of the report i.e. structuring messages in a coherent way.

- Sentence generation which involves generating natural language text to convey messages.

When a communicative goal is submitted, the Explanation Module determines what type of report to generate i.e. comparative report or sensitivity analysis report and what type of explanations to convey to the users (content determination). The natural language generator then chooses an appropriate text plan (see Figure 3 and Figure 4) and coherently structures the explanations (discourse planning). Text-based templates are selected using a set of rules and statistical techniques. These are filled with qualitative and quantitative values to produce explanations in natural language form (sentence generation).

Figure 3: Text plans for the Comparative Report

Figure 4: Text plan for the Sensitivity Analysis Report

The Explanation Module produces the following five types of explanations which are described in more detail in [9]. A summary is given in the appendix.

1. Model parameters.

2. Statistical comparisons.

3. Reasoning.

4. Knowledge representation.

5. Sensitivity analysis.

5 Moderated Decision Making Workshops

Decisions in the context of emergency and remediation management involve many parties who have different views and responsibilities [1,2,3,35,36]. Decision makers

(DMs) are those responsible for the decision. Stakeholders share, or perceive that they share, the impacts arising from a decision and therefore they claim that their perceptions should be taken into account. Experts provide economic, engineering, scientific, environmental and other professional advice. Analysts are concerned with the synthesis of the DMs' and stakeholders' value judgments and the experts' advice. In addition, they guide and assist the DMs and know how to operate the MCDA algorithms.

In Germany, new concepts of how to manage people and how people would like to be managed have arisen and "moderation" methods became popular [37,38]. The word "moderation" denotes a lessening of intensity or extremeness. Today, the moderation method is used in quality circles or CIP (Continuous Improvement Process) work as well as in conducting workshops, discussions and taskforce meetings. Depending on the specific circumstances, a complete moderation cycle can take between one hour and several weeks.

Since the identification of responsibilities and authorities is vital to implementing a rapid response in emergency and remediation management scenario-focused workshops involving key stakeholders are conducted as emergency exercises using "moderation" methods [1,38,39]. The moderators' responsibility is to lead the discussion in the workshops. They introduce the individual work steps with precisely formulated and visualized questions according to a flowchart. Furthermore, they steer the group with questions as the work continues and manage the interactions with and between participants. They do not comment on or judge contributions made by participants, but will always strive to actively include all members of the group in the work at hand (cf. [38]), similar to a facilitator [28]. While a facilitator is principally concerned with communication and maintaining group harmony, moderators more actively choose instruments (e.g. card inquiry) in order to foster the group's cooperation. The close relation between the phases of moderation and those of multi-criteria decision analysis is visualized in Figure 5 [37].

Figure 5: Steps of a moderation cycle and of multi-criteria decision analysis

6 The Scenario focused Workshop

A series of moderated workshops in the context of “Decision analysis of countermeasure and remediation strategies after an accidental release of radionuclides“ was organized in Finland, UK, Germany, Belgium, Slovak Republic, Poland and Denmark. One workshop focusing on agricultural countermeasure and remediation strategies was organized in collaboration with the Federal Office for Radiation Protection (BfS) in Freiburg, Germany. There were 18 participants, including officials and politicians of regional, state and federal authorities, who represented the different stakeholder and expert groups in emergency management in Germany.

In advance of the workshop, background material, an explanation of the introductory case study and preparatory information for using the evaluation software Web-HIPRE were sent to the participants. The RODOS system was used to calculate the necessary data for the hypothetical accident scenario before and during the workshop. The main objectives of the workshops were:

- Exploration of information and data requirements for the decision makers.
- Identification of the factors driving decision making in the context of agricultural nuclear emergency management.
- Application of the evaluation software Web-HIPRE and the Explanation Module.
- Development of methods for stakeholder involvement in exercises and emergency planning.

6.1 The hypothetical case study

The hypothetical radiological accident scenario forms the basis of the case study for one of the moderated decision making workshops in Germany. The fictitious contamination situation in the scenario was assumed to be caused by a serious accident at a nuclear power plant which triggered the immediate shutdown of the reactor. Starting four hours after the accident radioactive material was released into the atmosphere over a period of three hours. Further emissions were not expected according to plant operators. Figure 6 illustrates the contamination situation in the surrounding area of the nuclear power plant, detailed information on the (hypothetical) accident scenario are compiled in Table 1.

Table 1: The hypothetical accident scenario

Figure 6: Ground Contamination in the surrounding area of the power plant

After an analysis and forecast of the radiological situation the following emergency actions were implemented before the radioactive release started (see Figure 6 for the location of the different zones):

- Evacuation of inhabitants from the central zone.
- Sheltering of inhabitants in the intermediate zones M1, M2, M3 and outer zones A1, A2, A3, until the morning after the accident.
- Distribution of iodine tablets to children in the intermediate zones M1, M2, and M3.

With respect to agriculture and food the inhabitants in the affected districts received the following recommendations:

- Cover and/or close green houses and nurseries.
- Cover agricultural areas with vegetables, fruit and herbs.
- Cover open storages for animal feed and foodstuffs.
- Close animal stables and reduce ventilation.

Eight potential countermeasure and remediation strategies are examined within the fictitious accident scenario (cf. Table 2). The consequences (quantification of the respective benefits) which result from these different strategies are shown in Table 4. Whereas the data compiled in Table 4 directly result from the RODOS system the values compiled in Table 5 are estimated by the attending stakeholders and experts.

Table 4 and Table 5 contain the underlying values of the decision analysis within the workshop.

Table 2: Declaration of the alternative agricultural countermeasures

6.2 Problem structuring

The case study was analyzed and structured in a moderated discussion. At first, the workshop participants determined the relevant decision criteria from the list of criteria available in RODOS. Additional important criteria which are not provided by RODOS were identified by the experts and stakeholders on the regional, state and federal level via card inquiry. The selected criteria and their denotations are compiled in Table 3.

Table 3: Selected decision criteria and their meanings

Collecting, structuring and assorting of information during the discussion provided deeper insight into the core of the problems under scrutiny and lead to some form of shared understanding amongst all participants of the workshop. The structuring and modeling process resulted in an attribute tree (cf. Figure 7) which shows the overall goal ”total utility“ (of a measure) as the top criterion being split up into the criteria ”radiological effectiveness“, ”resources“, ”impact“ and “acceptance”, each of which is split up again.

Figure 7: Attribute tree for the exemplar case study. The abbreviations are declared in Table 2 and Table 3.

While the values of the attributes compiled in Table 4 directly result from the RODOS system, the values of the attributes listed in Table 5 were estimated by the attending stakeholders and experts. For the latter, a fictitious scale ranging from 0 to 100 is assumed where 100 corresponds to the highest value (resp. utility) and 0 to the lowest.

Table 4: Decision Table – Part 1 – values directly imported from RODOS

Table 5: Decision Table – Part 2 – values estimated by experts and stakeholders

6.3 Preference elicitation

As a first step of the preference elicitation, the weighting of the criteria of the attribute tree (cf. Figure 7) were carried out. The following preference weights were elicited in a group discussion using direct and SWING weighting [28,40]:

- "radiological effectiveness" vs. "resources" vs. "impact" vs. "acceptance":
  While formulating priorities in the workshop using the SWING method in Web-HIPRE the acceptance of a measure was given the highest rating (100 points). This choice was based on the premise that acceptance by the public, affected individuals and business have the highest relevance with respect to the specific decision, since together they form the critical foundation upon which future developments are built. The actual effects of a measure were given the second highest rating, based on the magnitude of the decision (size of affected area) and the consequences of the measure (amount of waste above the threshold, cost etc.). The radiological effectiveness was weighted only lightly in fourth place since it only plays a superficial role for agricultural measures.

- "population" vs. "worker":
  The maximum dose for the population is determined by estimating the intake of radioactivity through contaminated food. In this case the radiation dose for the workers is insignificant and additional exposure resulting from future measures is not expected.

- "avoided individual dose (adults – 1 year)" vs. "avoided individual dose (children – 1 year)" vs. "avoided collective dose" vs. "received collective dose":
  The different dose values are calculated based on the foodstuff milk under the assumption of 100% local production and consumption. Since milk with contamination above a certain intervention limit is banned from the market the maximum dose values calculated here are highly unlikely. Consequently the comparison of these values between measures with respect to radiological effectiveness can only be regarded as an indicator. As a result the avoided collective dose for one year receives the most importance in the evaluation of the

SWING method followed by the children avoided individual dose for one year. The remaining doses receive only a minor weighting.

- "max. individual dose received by worker" vs. "collective dose received by worker":

  In contrast with the calculated dose values for the population, the calculated dose values for the workers are directly related to the actual execution of the measure and thus contribute to the radiation exposure. This would indicate a strong weighting for the individual dose. However, since no significant radiation exposure during the implementation of the measure is expected, the maximum individual dose received by the worker and the collective dose are presumed equal.

- "# workers" vs. "supplies":

  The two attributes "# workers" and "supplies" are required to estimate the required resources of a measure. They receive approximately the same weighting with slightly more importance assigned to the number of workers. In essence both are equally significant for judging the measure, but they have different dimensions of a required resource.

- "total food above" vs. "food above yr-1" vs. "size of area" vs. "costs":

  The weighting within „impact" in order of importance was: size of area, total food above, cost and food above yr-1. Measures affecting agriculture are influenced to a very large degree by the size of the area involved. The less land involved, the easier decision making usually is. The total amount of waste produced also carries substantial importance due to its effects on judging the feasibility of a measure and on the criteria costs. Due to the large time period and the need for quick acceptance the "food above the limit" values after one year plays only a minor role.

- "public" vs. "affected producers" vs. "trade and industry":

  The highest weight within the category „acceptance" was given to the public, followed by industry and those affected by the measures. This ranking reflects the fact that the measures affect only a small area, with industry playing a larger role due to cooperation requirements. The public's large role is explained by the need for overall trust and consequently acceptance of future measures.

Subsequently, the value functions and their shape were defined for each individual attribute using both linear and exponential functions, as considered appropriate by the participants. Since the aim of the workshop was the creation of awareness, only qualitative results are reported. After the completion of the weight elicitation the question of whether a fixed attribute tree, containing information about a fixed set of relevant decision criteria and feasible countermeasures identified by stakeholders and experts, was desirable or whether an attribute tree should always by developed spontaneously in case of an emergency was raised for discussion.

6.4 Selected Results

Following the preference elicitation the composite priorities (cf. Figure 8) were calculated and illustrated by Web-HIPRE. Figure 8 shows that "rmov, T=0" is the most preferred alternative followed by "disp". While "acceptance" provides a large contribution to the good overall performance of both of these alternatives, "impact" is the most important factor in differentiating between them. Since the weights assigned to "radiological effectiveness" and "resources" are comparatively small, the differences in the overall scores which would provide reasons to favor "disp" over "rmov, T=0", do not have a big effect on the results of the analysis.

Figure 8: Results of decision analysis illustrated by Web-HIPRE

In addition, a sensitivity analysis on "acceptance" (cf. Figure 9) allows the examination of the robustness of the choice of an alternative relative to changes of the weight assigned to "acceptance". Moreover, the sensitivity analysis graph shows the range of weights for "acceptance" for which an alternative is the most preferred. Under the assumptions made above, the weight for "acceptance" can be changed by approximately 26 % without changing the optimality of "rmov, T=0". For a further reduction of the weight, "proc" turns out to be the best choice.

Figure 9: Sensitivity analysis in Web-HIPRE

Finally, the explanation module was used to generate comparative reports as well as sensitivity analysis reports to provide the results of the decision analysis in natural language format. In particular, a comparative report for "rmov, T=0" and "disp." allowed to gain deeper insight into the factors differentiating between the two alternatives. Figure 10 shows the comparison with respect to "impact" (an internal node of the attribute tree).

Figure 10: Extract of a comparative report

At the end of the workshop the participants were asked to fill in a questionnaire with statements about the suitability of decision making workshops for training and exercises for emergency situations. The general tendency of the responses was that the workshop was considered to be very useful for training purposes and that decision analysis helps to ensure the transparency of decisions and to understand the opinions and views of other participants (cf. Figure 11). In particular, many participating stakeholders emphasized that they perceived the sensitivity analysis as well as the comparative and sensitivity analysis reports as a valuable benefit for decision making because of the consequential deeper insight into the situation.

Figure 11: Selected results of the questionnaire

7 Conclusions

Complex decisions require input from various disciplines and fields of expertise. Especially in engineering, model building helps to bring together existing knowledge. Moreover, models can be used to simulate different parameter variations and thus to generate results in different scenarios. Many efficient planning tools for emergency management have been elaborated in the last years, but methods for the selection of the most suitable strategy are not much discussed in literature.

Emergency planning is of particular interest in nuclear power generation since, although the occurrence probability of an accident is considered to be low, the consequences can be severe and far-reaching. Thus, much effort has been spent on the development of a tool such as RODOS. Now the challenge is to test the developed tools with engineers in practice, or more generally with potential users, in order to ensure that the responsible persons become familiar with the tools and methods and to guarantee that the developments meet the requirements of the users. Thus, a series of decision making workshop focusing on the evaluation of countermeasure and remediation strategies in the event of a nuclear emergency was arranged across Europe. The workshops in Germany were organized in collaboration with the Federal Office for Radiation Protection (BfS) in Freiburg. Applying RODOS including Web-HIPRE in the workshops has highlighted the potential of the system. Furthermore, the workshops were successful in determining issues for the further developments of methodology and decision support tools. The feedback from the participating stakeholders and experts was very positive in general and the workshops were considered to be very useful for training purposes. Multi-criteria decision analysis was considered to be a suitable framework for supporting, structuring and documenting decision processes, for understanding and bringing together the opinions and perspectives of all participants with diverse background and expert knowledge and for providing transparency within emergency and remediation management. The explanation module, which generates reports to explain the results of the decision analysis, contributes to the direct involvement of the decision makers by enhancing the understanding of the evaluation process and subsequently increases the overall acceptance of the entire system. Furthermore, the generated reports form an audit trail and thus improve the traceability of decisions.

In order to improve the operational applicability of the RODOS system further developments of the multi-criteria decision support tool Web-HIPRE, integrated into RODOS as an evaluation subsystem (ESY), are necessary [8]. Although the transparency and consensus achieved within the workshop were perceived as a large advantage for emergency management in general, the methods and tools used were not able to reflect the sequential and iterative process of decision making in real life. For instance, decisions on whether or not removing cows out at feed are taken immediately whereas decisions on the processing of milk are discussed at a later date. Thus, methods for sequential decision making are required, including up-to-date measurements for each new decision. Moreover, the input data and parameters of a decision making model are subject to various sources of uncertainty. Thus, on the one hand, sensitivity analyses are important for the robustness of decisions and, on the other hand, advanced multi-criteria methods taking approaches for uncertainty modeling into account are needed. In the course of continuously improving the system, the methods and tools need to be tested and evaluated by potential users of RODOS and Web-HIPRE in further decision making workshops in order to ensure that new developments always focus on the needs of the decision making process.

Since (nuclear) emergency and remediation management are typical multi-criteria problems involving economic, ecological and engineering questions as well as global political and socio-psychological issues, the described interdisciplinary approaches, which are in general universally applicable, can easily be transferred to other areas being tangent to any of these topics.

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Appendix

Explanations of the model's parameters

The Explanation Module codifies the decision model in two forms: qualitative e.g. the structure of the attribute tree and quantitative e.g. weights. Explanations of the model's parameters communicate the values of decision parameters such as the scores of the alternatives and the weights of the attributes taking into account the structure of the attribute tree and therefore relationships between attributes (e.g. whether an attribute is linked to a root node or an internal node). An example of this type of explanation follows:

- *Radiological effectiveness with respect to the worker(s)* accounts for 10.0 percent of the determination of *radiological effectiveness* and for 1.15 percent of the determination of *total utility*.
- **Disposal** rates 12.22 relative to *size of affected area* on a scale from 0 to 100.

This type of explanations can assist DMs in reviewing and refining the parameters of the decision model. If they are not satisfied with the verbally explained results, they can interact with Web-HIPRE and modify the values of the decision parameters (e.g. attribute weights or strategy scores).

Statistical explanations

Statistical explanations focus on determining those decision parameters that are significant or important in the ranking of strategies. They are based on statistical interpretations [34] of the decision model. Decision parameters that influence the final ranking are attribute weights, strategy scores and absolute differences between strategy scores. For example, in order to describe how good a remediation strategy is relative to the objective of increasing avoided individual radioactive dose, the following text template is generated by the Explanation Module:

<Strategy id> provides <semantic quantifier> <Objective> in the context of all available strategies.

A semantic quantifier is a verbal expression (such as “substantially better”, “slightly worse” and “significant”) that describes the quality of a parameter and can be determined in the following way. Given an objective, the mean μ and the standard deviation σ of the scores of all available strategies relative to this objective can be calculated. Assuming that the score of a remediation strategy (e.g. “rmov, T=0”, i.e. “Removal of cows from contaminated feed at time T = 0, feeding with uncontaminated feed”, see Table 2) is s = 5 on a scale from 0 to 100, the quality of the strategy can be described by mapping s (i.e. the score of the strategy) to a discrete set of semantic quantifiers: {“very good”, “neither very good nor very poor”, “very poor”} as follows (λ is a user-defined constant):

if $s > \mu + \lambda\sigma$ → “very good”

if $\mu - \lambda\sigma \leq s \leq \mu + \lambda\sigma$ → “neither very good nor very poor”

if $s < \mu - \lambda\sigma$ → “very poor”

An explanation generated by the system can be:

- **rmov, T=0** provides very poor *avoided individual dose (adults, 1 year)* in the context of all available alternatives.

Statistical explanations help DMs to concentrate on those aspects that are significant in the decision process and therefore considerably reduce the time needed for parameter assessment.

Explanations of reasoning

Explanations of reasoning focus on describing how conclusions are derived from the formal mathematical model employed by the system. These explanations can discriminate factors that support a choice from factors that do not. For example:

- While *resources* is the main reason to prefer **disposal**, this is outweighed by considerations of *impact*, along with other less important factors, that provide reasons for preferring **rmov, T=0**.

The system generates the above type of explanation by calculating the value differences i.e. the differences of the value functions of the two strategies (i.e. disposal and rmov, T=0) relative to all the objectives. There is a reason to prefer disposal if there is at least one positive value difference. If there are more than one positive value differences then the objective with the highest positive difference (in this case resources) is the main reason to prefer disposal. The main reasons to prefer rmov, T=0 are identified by interpreting the negative value differences in a similar way.

Another example of this type of explanation is as follows:

- While *impact* is not particularly important in determining *total utility*, **disposal** differs sufficiently from **rmov, T=0** on *impact* which makes it a significant factor in this case.

Explanations of reasoning provide an overall assessment of the decision model and offer valuable insight into the problem at hand. They illustrate the most significant factors in the ranking of alternatives and highlight arguments for or against a choice.

Knowledge representation

Such explanations convey qualitative information, illustrate the structure of the attribute tree and describe the attributes and alternatives taken into account. Text is generated taking into account the structure of the attribute tree as well as information about attributes and remediation strategies. Examples of this type of explanation follow:

- This judgement takes into account the effects of *rad. effectiven.*, *resources*, *impact* and *acceptance*.

- Comparison of **disposal** and **rmov, T=0** with respect to *total utility* and *rad. effectiven.*.

Such explanations highlight how the attribute tree is structured and outline the attributes taken into account in the ranking of remediation strategies. They help DMs identify attributes that appear to be less important but nevertheless are being considered. This can be helpful when DMs consider agricultural countermeasures in the medium phases of a nuclear emergency and may have to consider a large number of attributes.

Knowledge representation explanations include descriptions of attributes and alternatives (also called strategies). There are currently plans to provide more detailed descriptions of the remediation strategies that are taken into account in the evaluation process.

Sensitivity analysis explanations

These explanations interpret the sensitivity analysis graphs plotted by Web-HIPRE. They describe the sensitivity analysis graph, discuss the optimality of strategies and give the values of decision parameters for different values of the weight of an attribute. An example follows:

Sensitivity Analysis for *total utility* on the weight of *rad. effectiven*.

This analysis examines how robust the choice of an alternative is to changes of the weight of *rad. effectiven*..

The lines in the graph of the sensitivity analysis, each associated with one strategy, show the weighted scores of the (associated) strategies when the weight of *rad. effectiven*. is varied from 0% to 100%. The vertical line at 11.54 represents the status quo. The overall scores of the alternatives are:

…

The percentage on *rad. effectiven*. can be changed by as much as 11.81% without changing the optimality of **rmov, T=0**.

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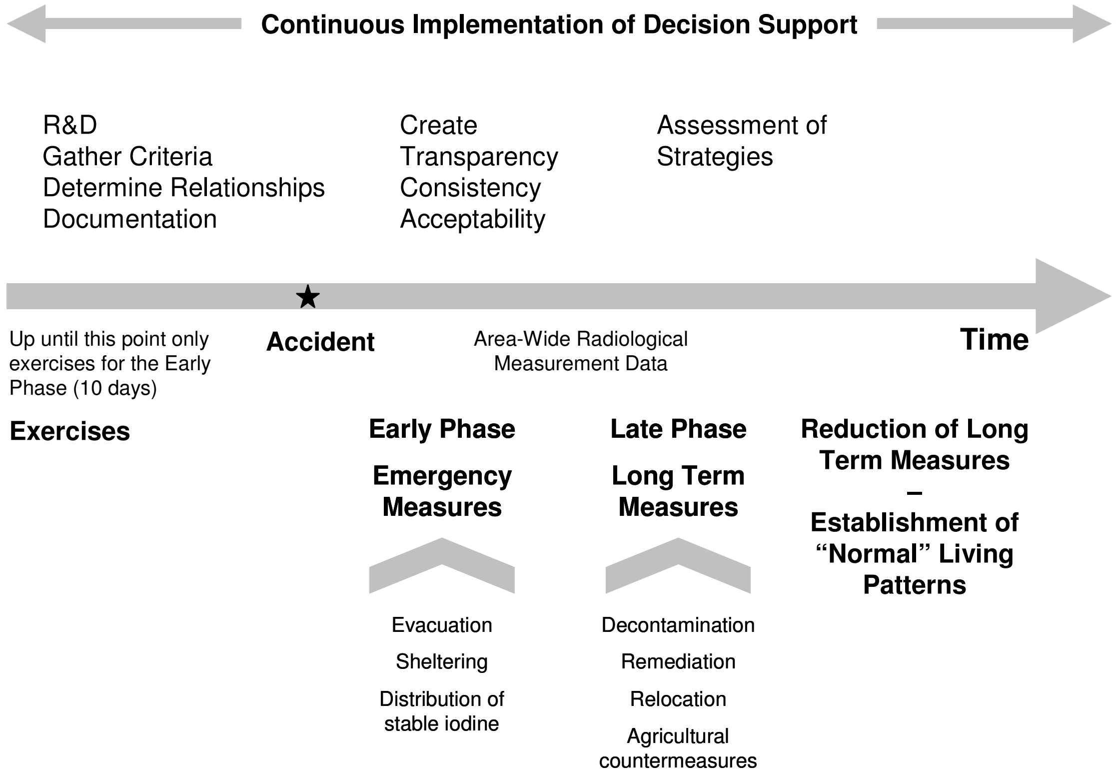


Figure 1: Implementation of decision support throughout all phases of emergency management

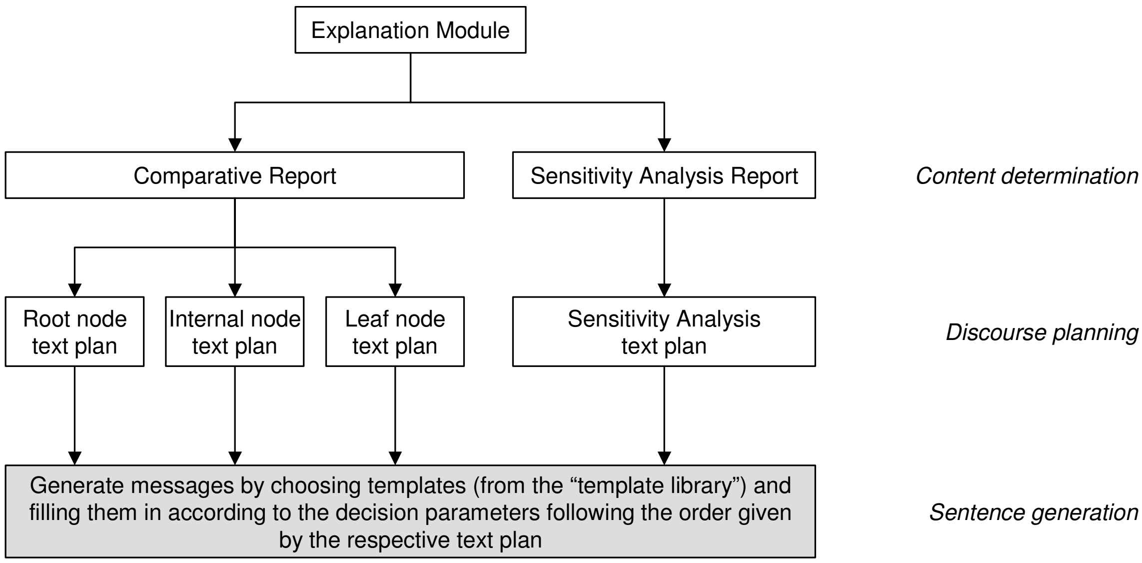


Figure 2: The general structure of the Explanation Module

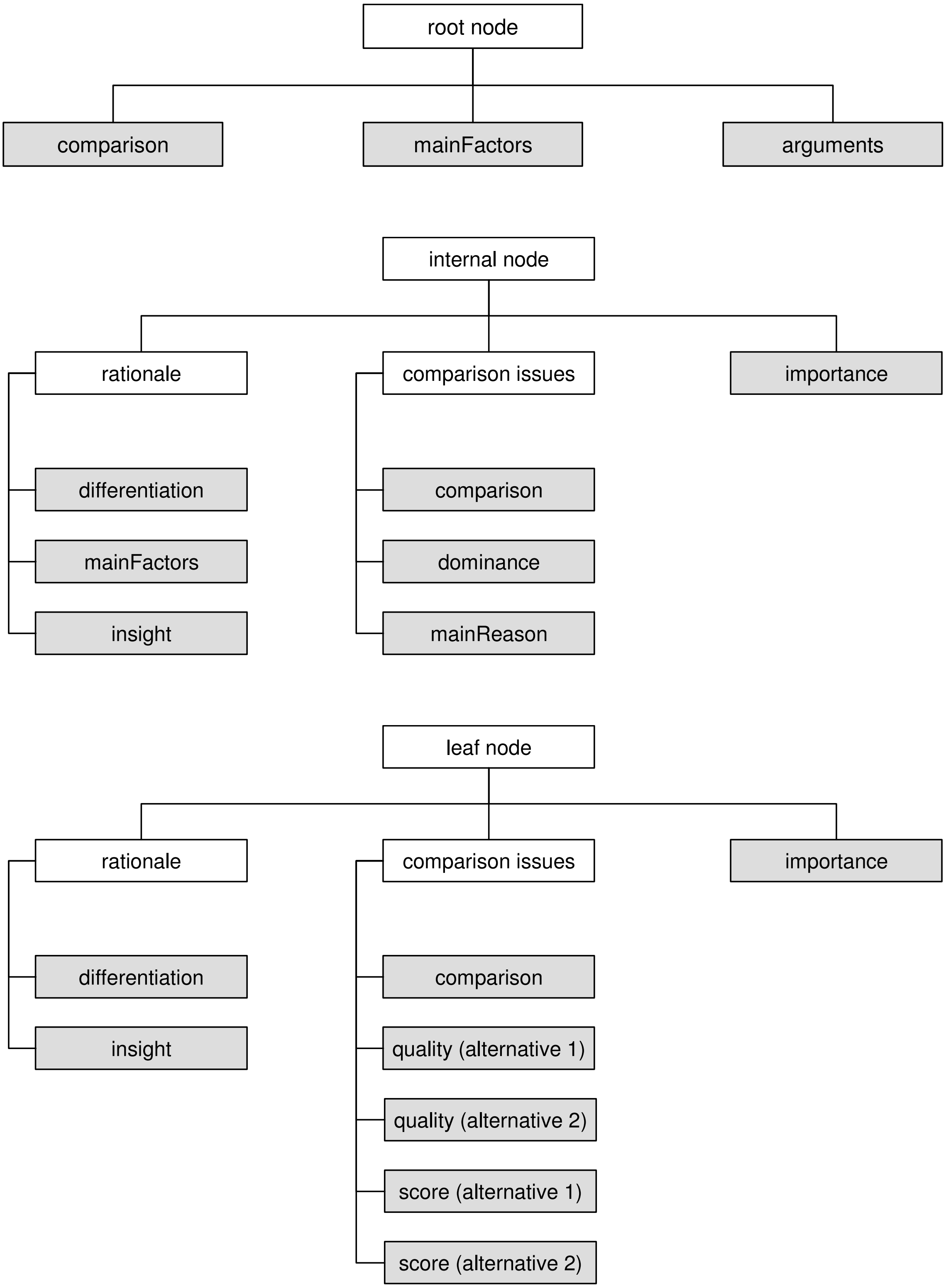


Figure 3: Text plans for the Comparative Report

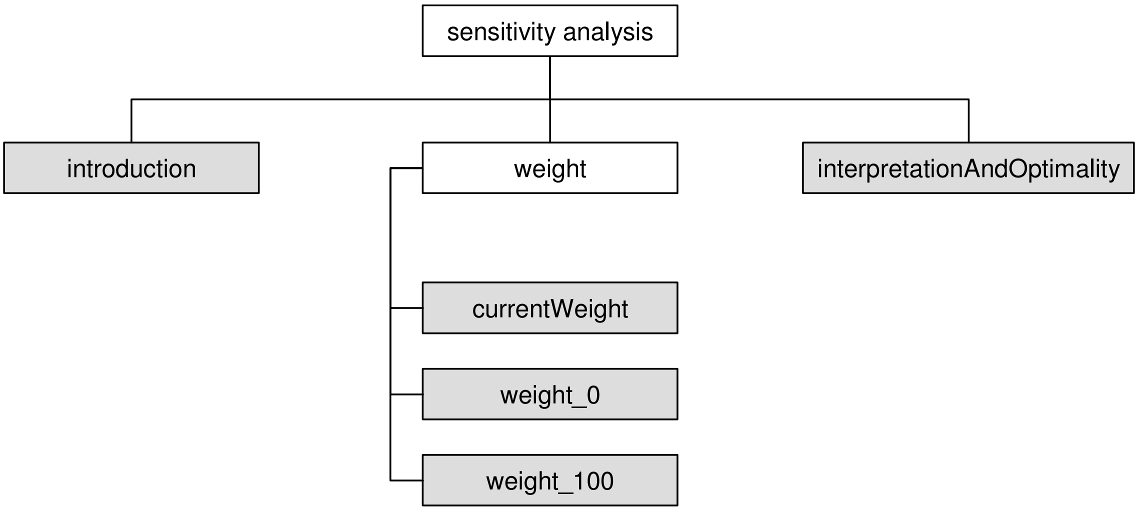


Figure 4: Text plan for the Sensitivity Analysis Report

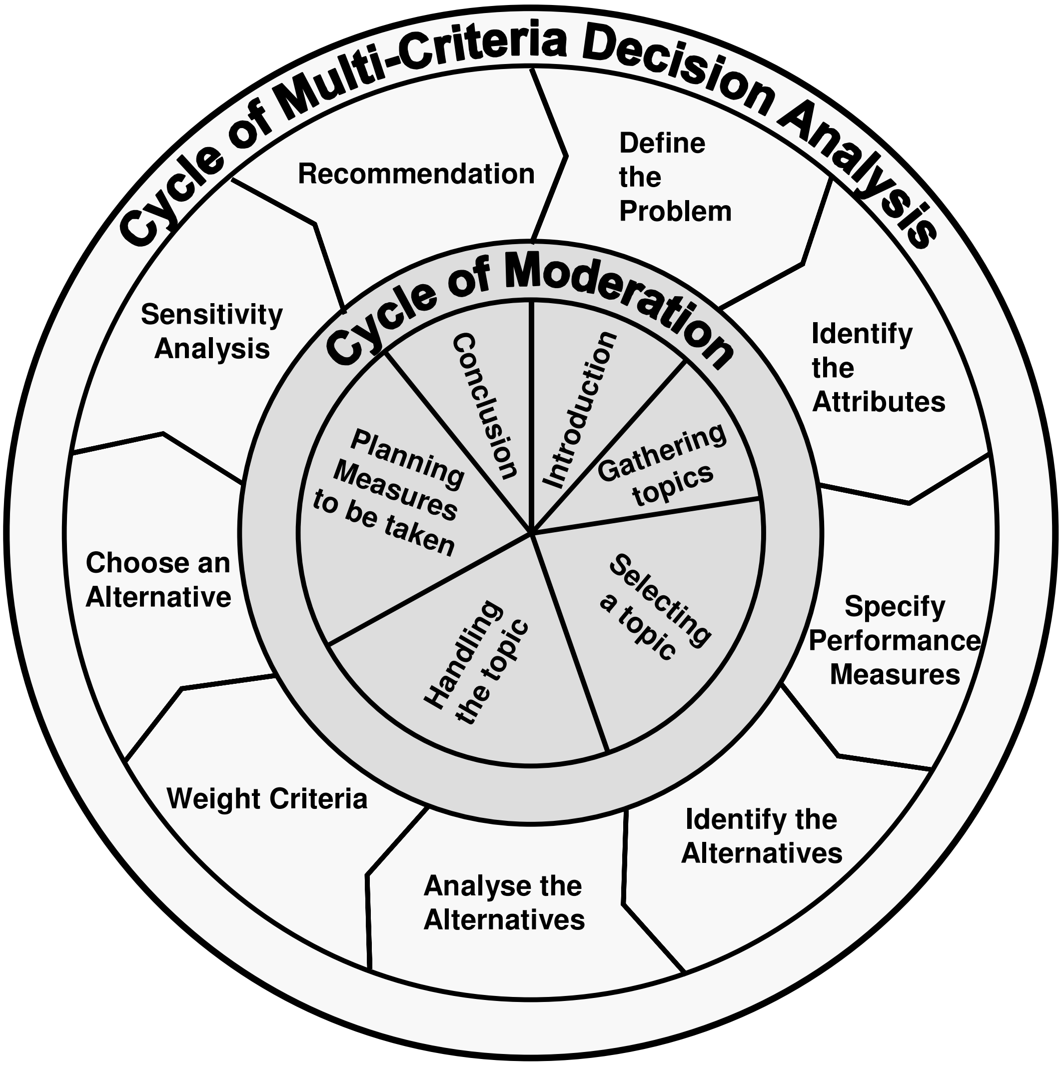


Figure 5: Steps of a moderation cycle and of multi-criteria decision analysis

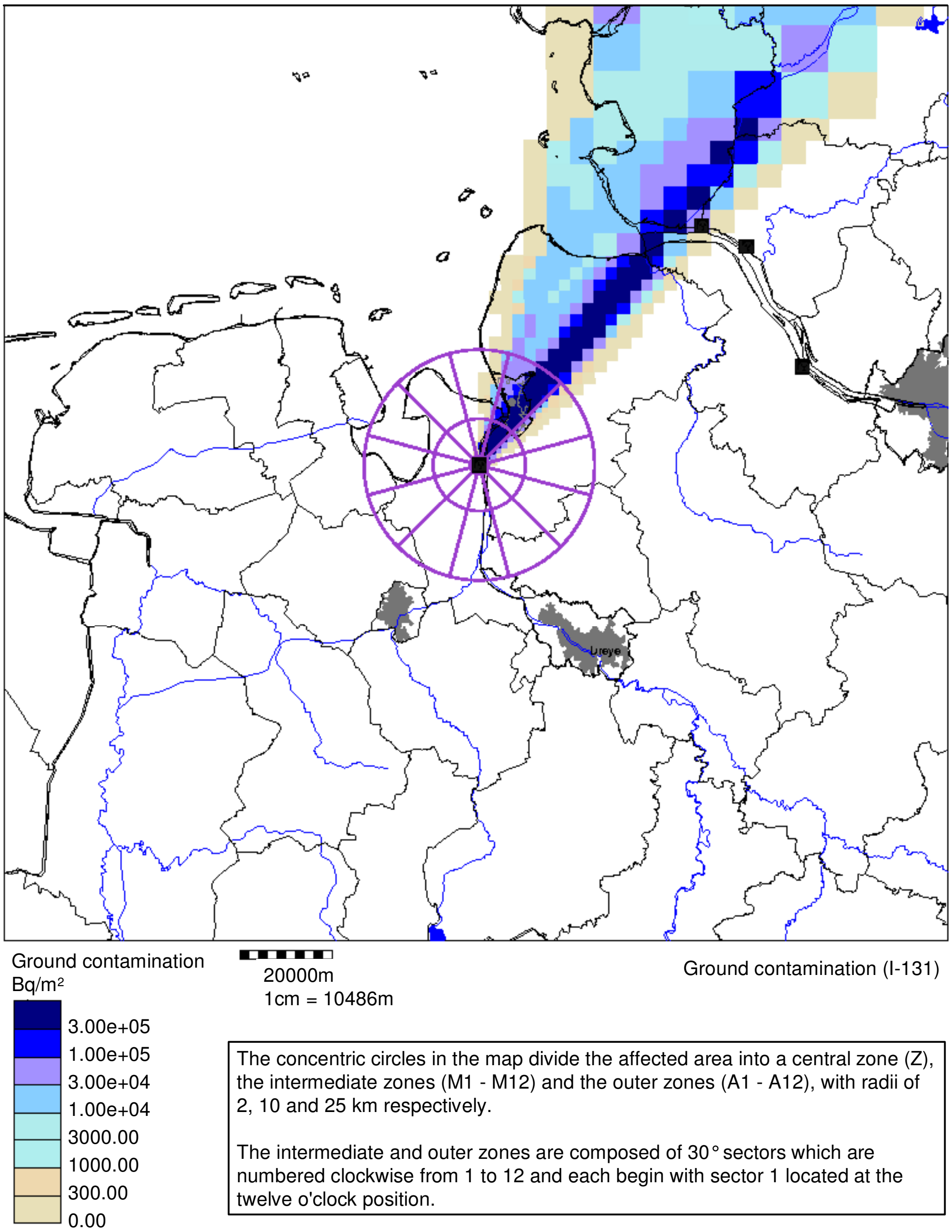


Figure 6: Ground Contamination in the surrounding area of the power plant

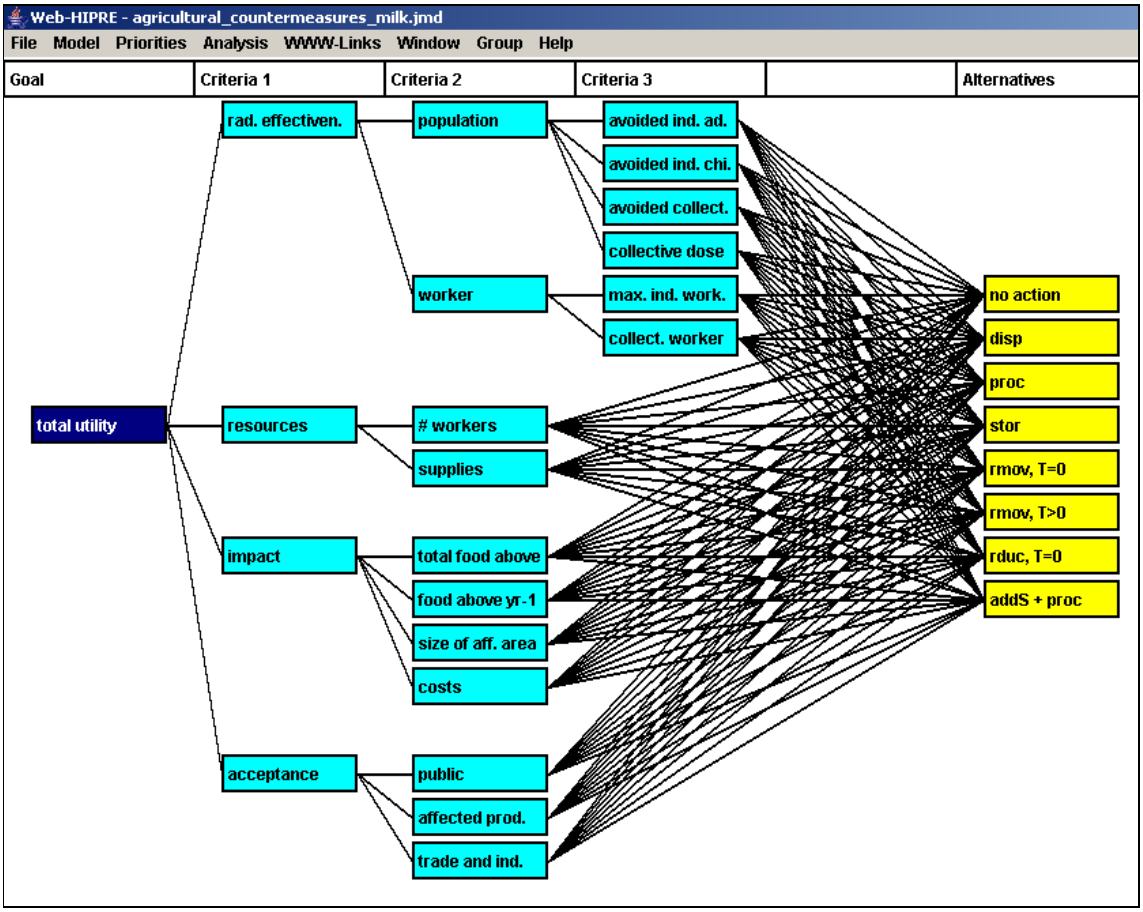


Figure 7: Attribute tree for the exemplar case study. The abbreviations are declared in Table 2 and Table 3.

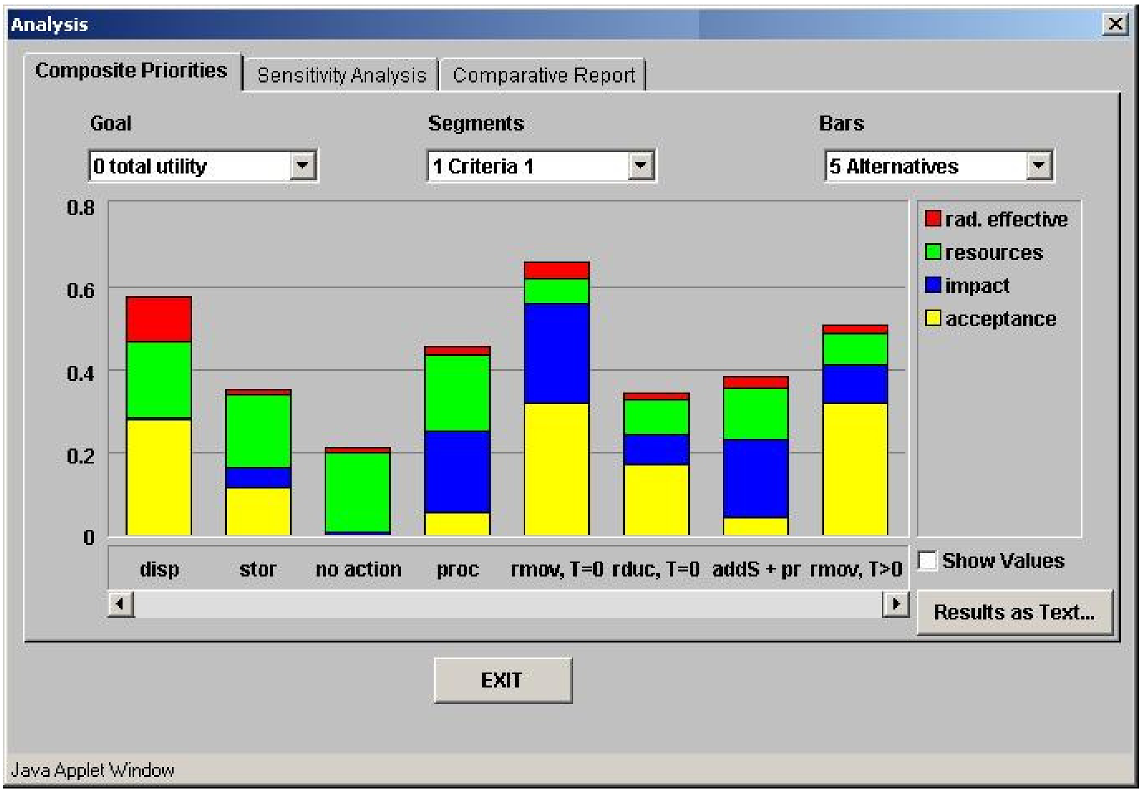


Figure 8: Results of decision analysis illustrated by Web-HIPRE

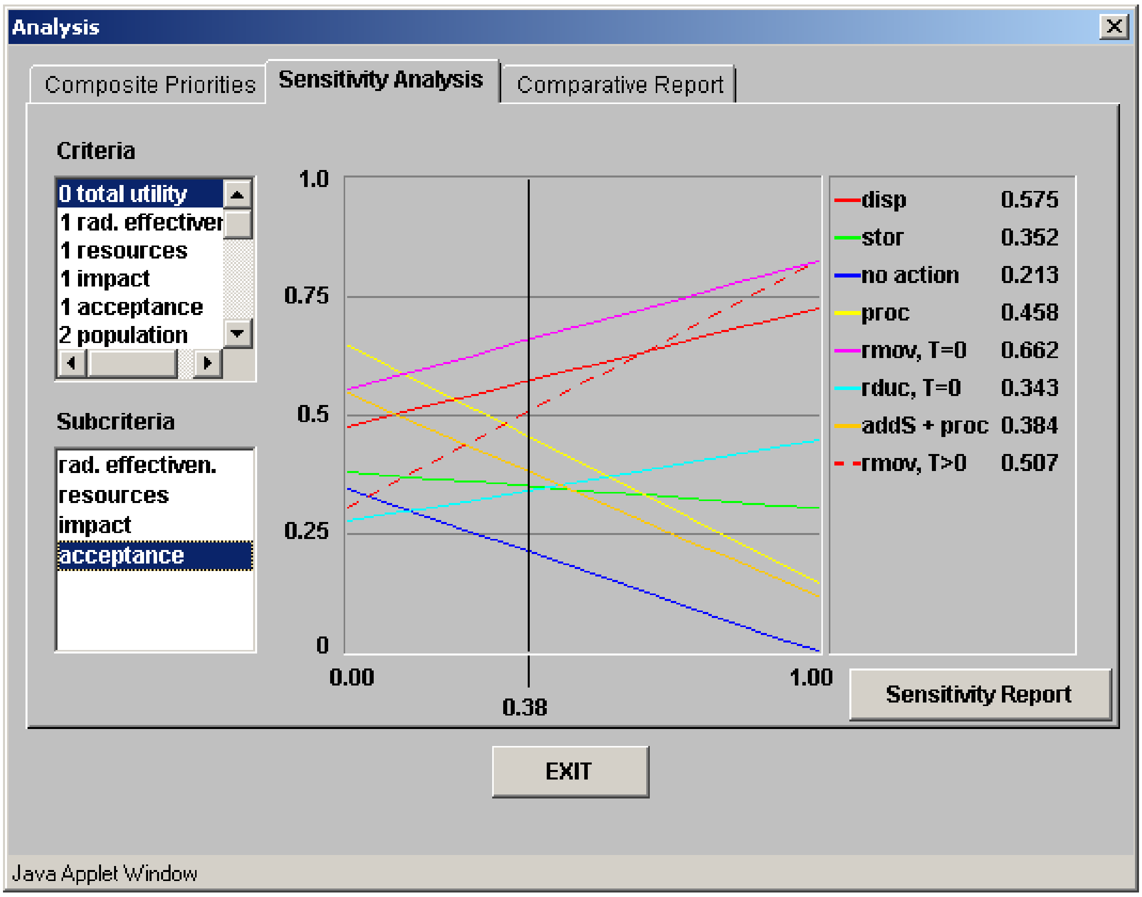
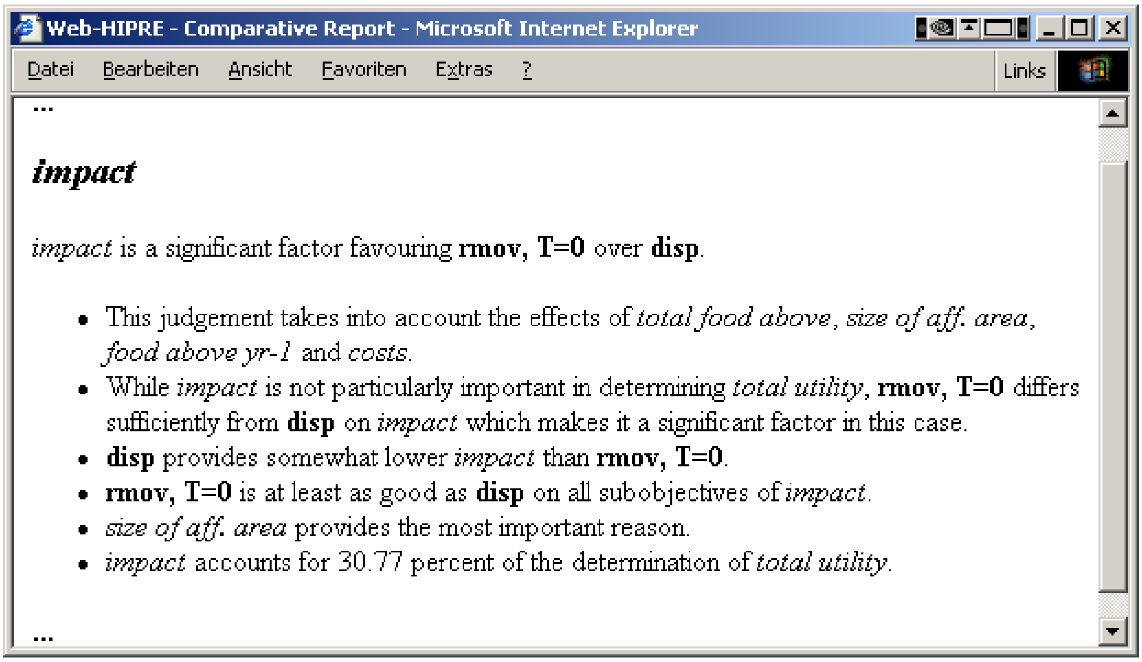


Figure 9: Sensitivity analysis in Web-HIPRE



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impact

impact is a significant factor favouring **rmov, T=0** over **disp**.

- This judgement takes into account the effects of *total food above*, *size of aff. area*, *food above yr-1* and *costs*.
- While *impact* is not particularly important in determining *total utility*, **rmov, T=0** differs sufficiently from **disp** on *impact* which makes it a significant factor in this case.
- **disp** provides somewhat lower *impact* than **rmov, T=0**.
- **rmov, T=0** is at least as good as **disp** on all subobjectives of *impact*.
- *size of aff. area* provides the most important reason.
- *impact* accounts for 30.77 percent of the determination of *total utility*.

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Figure 10: Extract of a comparative report

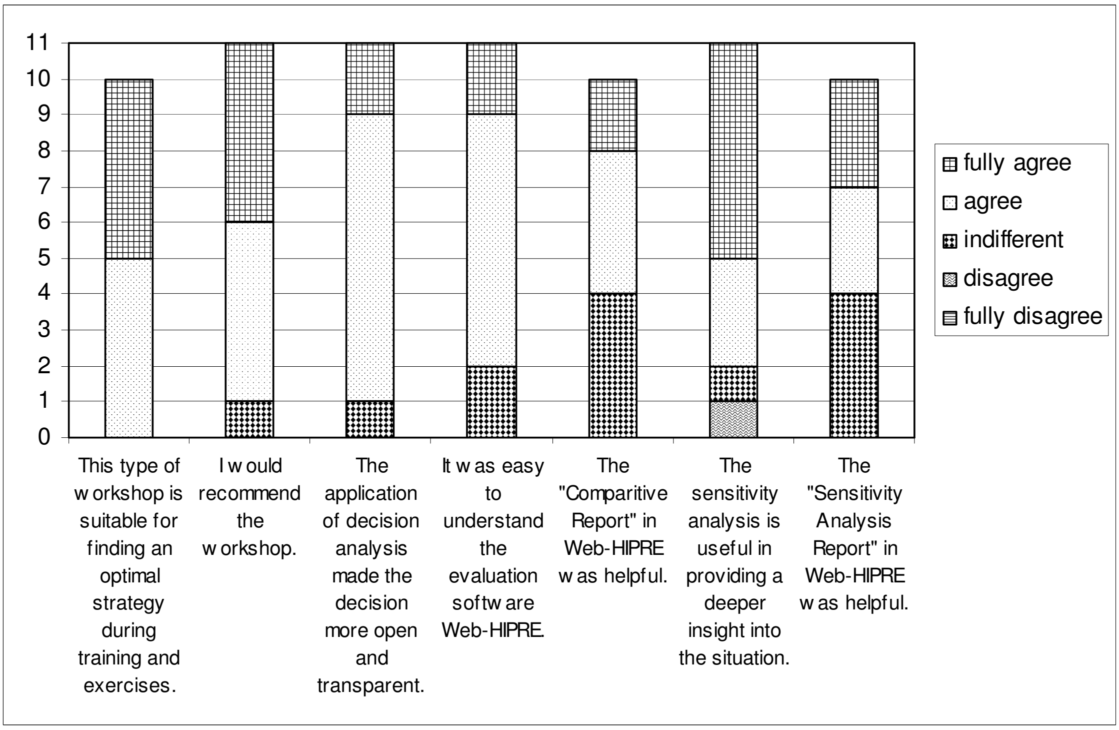

Figure 11: Selected results of the questionnaire

Table 1: The hypothetical accident scenario

Meteorological situation:

Due to south-westerly winds the radioactive cloud from the nuclear power plant was blown over agricultural areas in a north easterly direction. As a result, radioactive material from the cloud deposited onto the ground. While the cloud passed heavy precipitation and even thunderstorms were observed. Three hours after the radioactive emissions were stopped the radioactive cloud crossed the German border into a neighboring country. After this point in time all air monitoring stations in Germany reported normal levels of radioactivity in the atmosphere.

Radiological situation:

According to initial estimations by plant operators the cloud contained radioactive noble gases (approx. 50% of the plant inventory), radioactive iodine and radioactive aerosols (each making up approx. 0.075% of the plant inventory, the iodine fully in elementary form). In the most affected area, the measured local dose on the morning after the accident reached 1000 µSv/h (micro Sievert per hour) 1 km from the plant, 200 µSv/h at a distance of 10 km and 50 µSv/h 25 km away. In all other affected areas of the district the local doses ranged between 0.01 and 50 µSv/h. This is roughly equivalent to a ground concentration of 1 to 3000 kBq/m^2 (kilo Becquerel per square meter) for I-131 and 0.1 –300 kBq/m^2 for Cs-137, when taking into account the actual nuclide spectrum.

Explanation of the units:

Sievert (symbol Sv) is a unit of equivalent dose or effective dose (of radiation), and thus depends on the biological effects of radiation as opposed to the physical aspects, characterized by the absorbed dose (which is measured in Grays) whereas Becquerel (symbol Bq) is a unit of radioactivity, defined as the activity of a quantity of radioactive material in which one nucleus decays per second and is thus equivalent to s^{-1}.

Table 2: Declaration of the alternative agricultural countermeasures

Abbreviation	Meaning
no action	no action
disp	Disposal (of the produced milk)
proc	processing (of milk)
stor	storage
rmov, T=0	removal of cows from contaminated feed at time T=0, feeding with uncontaminated feed
rmov, T>0	removal of cows from contaminated feed at time T>0, feeding with uncontaminated feed
rduc, T=0	animals are given uncontaminated / less contaminated feed
addS + proc	adding of concentrates to the food which reduce the activity concentration (of milk and meat) and subsequent processing

Table 3: Selected decision criteria and their meanings

Abbreviation	Meaning
total utility	total utility of a measure (with respect to milk)
rad. effectiven.	radiological effectiveness
population	radiological effectiveness with respect to the population
avoided ind. ad.	avoided individual dose (adults - 1 year)
avoided ind. chi.	avoided individual dose (children - 1 year)
avoided collect.	avoided collective dose
collective dose	received collective dose
worker	radiological effectiveness with respect to the worker(s)
max. ind. work.	max. individual dose received by worker
collect. worker	collective dose received by worker
resources	necessary resources to conduct a measure
# workers	necessary number of workers needed to conduct a measure
supplies	Supplies (e.g. (agricultural) machinery) required to conduct a measure
impact	impact of a measure
total food above	total amount of food above the limit
food above yr-1	amount of food above the limit after 1 year
size of aff. area	size of affected area
costs	costs to conduct a measure
acceptance	acceptance of a decision
public	acceptance of a decision by the public
affected prod.	acceptance of a decision by the affected producers (e.g. agriculturists)
trade and ind.	acceptance of a decision by trade and industry

Table 4: Decision Table – Part 1 – values directly imported from RODOS

	no action	disp	Proc	stor	rmov, T=0	rmov, T>0	rduc, T=0	addS + proc
avoided ind. ad. [mSv]	0	6.77E-1	1.44E-2	3.16E-5	1.20E-2	4.50E-3	1.69E-3	4.10E-2
avoided ind. chi. [mSv]	0	1.35	2.88E-2	6.32E-5	2.39E-1	9.00E-3	3.30E-3	8.10E-2
avoided collect. [manSv]	0	1.20E+4	1756.62	71.0215	6194.81	1.58E+3	1.14E+3	2.56E+3
collective dose [manSv]	1.26E+4	7.89E+2	1.09E+4	1.26E+4	6.48E+3	1.11E+4	1.15E+4	1.01E+4
max. ind. work. [mSv]	0	0	0	0	1.25E-3	9.01E-4	1.07E-3	0
collect. worker [manSv]	0	0	0	0	2.42	6.14E-1	7.88E-1	0
# workers [#]	0	0	0	0	658	532	547	0
total food above [kg]	1.12E+8	1.12E+8	1.61E+7	1.12E+8	4.86E+7	8.3E+7	1.08E+8	1.46E+7
food above yr-1 [kg]	1.22E+5	1.22E+5	0	1.60E+3	3.12E+3	3.12E+3	3.12E+3	0
size of aff. area [km^2]	2640	2640	1787	2640	179	2640	2615	1787

Table 5: Decision Table – Part 2 – values estimated by experts and stakeholders (on a fictitious 0-100 scale)

	no action	disp	proc	stor	rmov, T=0	rmov, T>0	rduc, T=0	addS + proc
supplies	0	10	10	20	40	40	30	80
costs	90	100	20	50	20	20	20	35
public	0	100	5	15	80	80	30	5
affected prod.	0	20	70	60	100	100	80	50
trade and ind.	0	40	5	50	80	80	60	5