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Applications

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. This work highlights 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. Decision support is enhanced by a module that generates natural language explanations to facilitate the understanding of the evaluation process, therefore contributing to the direct involvement of the decision makers, 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 and remediation management; Multi-criteria evaluation; 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. Multi-criteria decision analysis (MCDA) can help to ensure transparency during the decision making process

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[1–5]. 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 (DMs) in 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 remediation management in the later phases after a nuclear or radiological emergency in Europe. One system that offers comprehensive support in managing nuclear or radiological incidents is the real-time on-line decision support system RODOS (see Section 2). 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 [6–8], was recently integrated into RODOS providing support in transparently and coherently evaluating the overall efficacy of possible countermeasure and remediation strategies [2,9] (see Section 3). Furthermore, an "Explanation Module" [10,11], 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 (see Section 4). 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. Section 5 deals with the combination of MCDA and moderation techniques in such a decision making workshop. Furthermore, the hypothetical case study which was used in a German workshop, the course of action and selected results are described in this section. Finally, Section 6 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 [12–15]. 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 drawbacks of various countermeasure strategies and their ranking according to the societal preferences as perceived by the DMs [12,13,15]. The system is characterized by its conceptual architecture which consists of the following three subsystems [14]:

- 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 DMs.

In the early phase, emergency management involves decisions on emergency actions, such as evacuation, sheltering or distribution of stable iodine, 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. 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 [16].

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 [17–19]. However, in this paper, we focus on the ESY and thus on the use of MCDA in nuclear emergency management.

3. Multi-attribute value theory (MAVT) and Web-HIPRE

MCDA supports the structured evaluation and support of decision problems with multiple criteria and uncertainty (see e.g. [5,20]). 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 [21]. 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 direct point allocation. The multi-attribute evaluation tool Web-HIPRE supports all the common weighting methods based on relative comparisons such as the SWING procedure [22], the SMART method [22,23], or SMARTER [24,25]. The analytic hierarchy process (AHP) (see [26]) is a decision modeling approach developed in parallel with the MAVT method. Its fixed comparison procedure based on a nine-point-scale 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 [27]. Thus, one can consider AHP as one MAVT method in the MCDA approach. For comparison and details of the use of different methods see [28,29]. Web-HIPRE allows any combination of these weighting methods in one model. There is 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. They are easy to perform with the support of Web-HIPRE [8,30]. 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 Figs. 3–5 (Section 5). 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.

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 [31]. They have proven to be useful to experienced professionals as well as to novices [32]. They influence user perceptions such as trust, confidence and satisfaction and increase levels of acceptance and learning [33].

An Explanation Module has thus been developed to justify the advice of the evaluation subsystem of RODOS and to increase the trust and confidence of

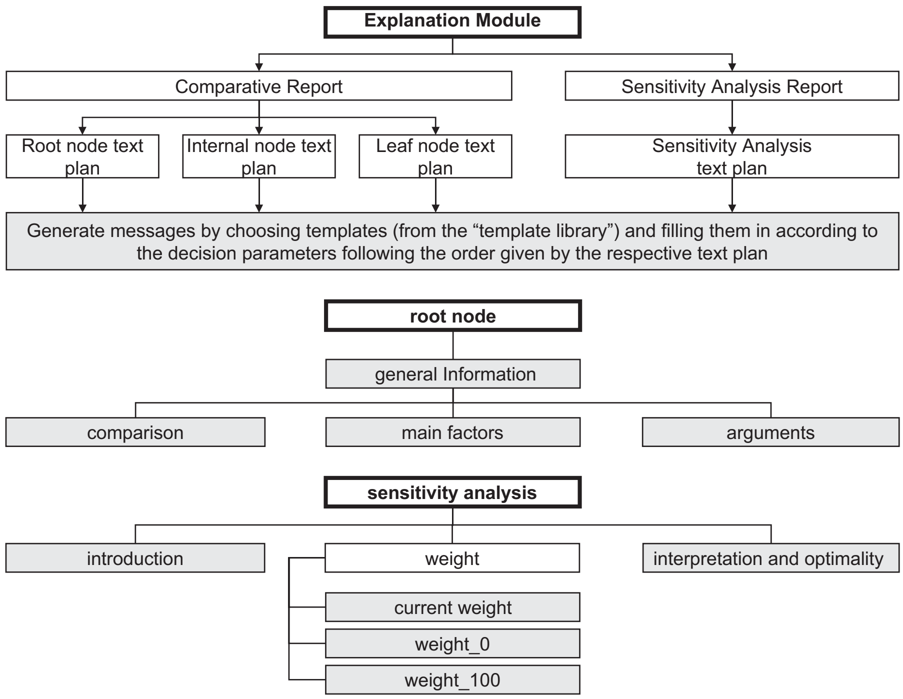


Fig. 1. Structure of the Explanation Module (top), Comparative report text plan for root node (middle), text plan for sensitivity analysis report (bottom).

the DMs in the results of the system [10]. In practice, the executive DMs do usually 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 reports:

- A "comparative report" that interprets the evaluation results and compares two strategies by discussing how well a strategy rates with respect to 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 results.

Fig. 1 (top) illustrates the general structure of the Explanation Module. Its input comprises qualitative data in the form of an attribute tree as well as quantitative data in the form of a decision table (containing the scores of the alternative strategies) or in the form of values of decision parameters (such as the weights). The Explanation Module then applies natural language techniques [34] and statistical methods [35] to generate understandable reports in English. 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 the 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 (cf. Fig. 1):

- *Content determination* which involves what type of report to generate (i.e. comparative report or sensitivity analysis report) and what type of explanations to convey to the users.
- *Discourse planning* which involves establishing the structure of the report i.e. structuring messages in a coherent way by choosing an appropriate text plan (Fig. 1 exemplarily illustrates the text plans for a root node and the sensitivity analysis report).
- *Sentence generation* which involves selecting text-based templates and filling in qualitative and quantitative values to produce explanations in natural language form in order to convey messages.

The Explanation Module produces five types of explanations: (1) model parameters, (2) statistical comparisons, (3) reasoning, (4) knowledge representation and (5) sensitivity analysis.

The statistical explanations for example, focus on determining those decision parameters that are significant or important in the ranking of strategies. They are based on statistical interpretations [35] of the decision model. Decision parameters that influence the final ranking are attribute weights, strategy scores and absolute differences between strategy scores. For instance, 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") 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 (where λ is a user-defined constant):

if $s > \mu + \lambda\sigma$ $\rightarrow$ "very good",

if $\mu - \lambda\sigma = s = \mu + \lambda\sigma$ $\rightarrow$ "neither very good nor very poor",

if $s < \mu - \lambda\sigma$ $\rightarrow$ "very poor".

An explanation generated by the system can be

Rmov, $\mathbf{T=0}$ 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. More details about the generation of explanations are given in [10].

5. The moderated decision making workshop

Decisions in the context of emergency and remediation management involve many parties who have different views and responsibilities [1–3,36,37]. 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. Thus, there is a need to *facilitate* or *moderate* the group decision making process. The responsibility of a *moderator* is to lead the discussion within a group, to introduce the individual work steps with precisely formulated and visualized questions (e.g. using a flowchart) and to strive to actively include all members of the group in the work at hand (cf. [38]). Moderators are often assisted by analysts who are concerned with the synthesis of the DMs' and stakeholders' value judgments as well as the experts' advice and know how to operate the decision support tools and algorithms. As a tool to help moderators and analysts to structure a group discussion, to defuse emotion and to focus on the essential dissensions, MCDA techniques have proven useful [5,39,40]. Furthermore, a close relation between the phases of moderation and those of MCDA can be observed [41].

Since the identification of responsibilities and authorities is vital to implementing a rapid response in emergency and remediation management (see e.g. [42]), a series of moderated workshops on "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. The workshops were conducted as emergency exercises on the basis of a hypothetical accident scenario using "moderation" methods [1,38,43]. RODOS was used to calculate the necessary data before and during the workshops. The main general objectives of the workshops were the exploration of information and data requirements for the DMs as well as the identification of the factors driving decision making in the context of agricultural nuclear emergency management. Furthermore, the workshops were aimed at gaining experiences in applying the evaluation software Web-HIPRE including the Explanation Module and at developing methods for stakeholder involvement in exercises and emergency planning.

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,

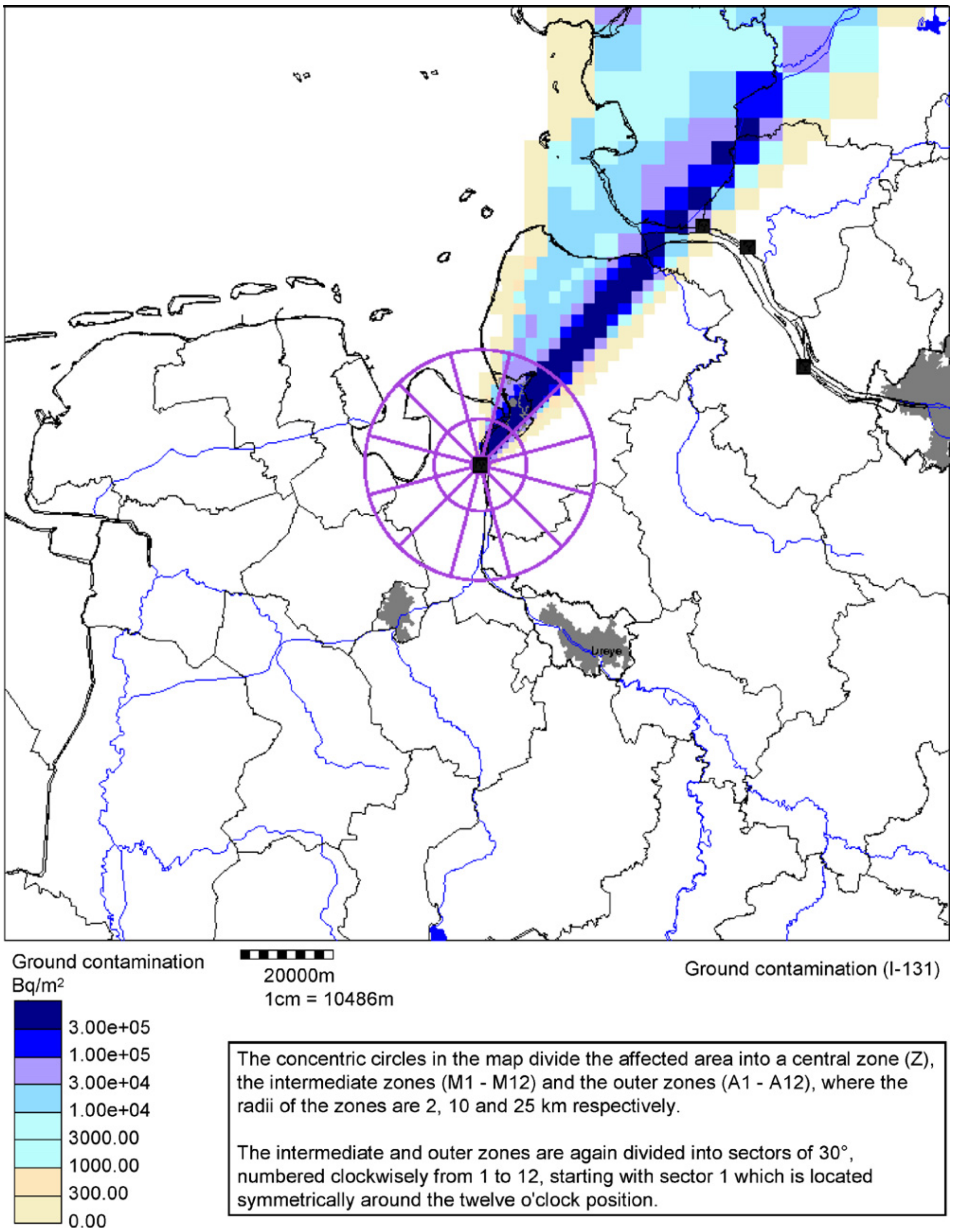


Fig. 2. Ground contamination in the surrounding area of the power plant.

including officials and politicians of regional, state and federal authorities, who represented the different stakeholder and expert groups in emergency management in Germany.

5.1. The hypothetical accident scenario

A hypothetical radiological accident scenario formed the basis of one of the German workshops. 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. A few hours after the accident, radioactive material was released into the atmosphere. The radioactive cloud from the nuclear power plant was blown over a larger area with important food production. As a result, radioactive material from the cloud deposited onto the ground. Fig. 2 illustrates the contamination situation

Table 1
Selected decision criteria and their meanings

Abbreviation	Meaning
Total utility	Total utility of a measure (with respect to milk)
Rad. effective.	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.	Maximum individual dose received by worker
Collect. worker	Collective dose received by worker
Resources	Necessary resources to conduct a measure
No. of 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

(as calculated by the ASY of RODOS) in the surrounding area of the nuclear power plant.

For the discussion within the workshop, it was assumed that all necessary immediate and early countermeasures (emergency actions) were initiated in selected affected areas. These included distribution of stable iodine to children and adults, sheltering or evacuation. Moreover, the closure of green houses and animal stables and the coverage of agricultural areas with vegetables, fruit and herbs, and of open storage for animal feed and foodstuffs were recommended.

5.2. Problem structuring

The case study was analyzed and structured in a moderated discussion. The relevant decision criteria were determined by the workshop participants 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 1.

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. Fig. 3) 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.

Fig. 3 also shows that eight potential countermeasure and remediation strategies were examined. The consequences (quantification of the respective benefits) which result from these different strategies are shown in Table 2. While the data compiled in Table 2 directly result from the RODOS system the values compiled in Table 3 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.

5.3. Preference elicitation

As a first step of the preference elicitation, the weighting of the criteria of the attribute tree (cf. Fig. 3) were carried out. The following preference weights were elicited in a group discussion using direct and SWING weighting [29,44]:

- "radiological effectiveness" vs. "resources" vs. "impact" vs. "acceptance":
  While formulating priorities in the workshop using the SWING method in Web-HIPRE the acceptance of

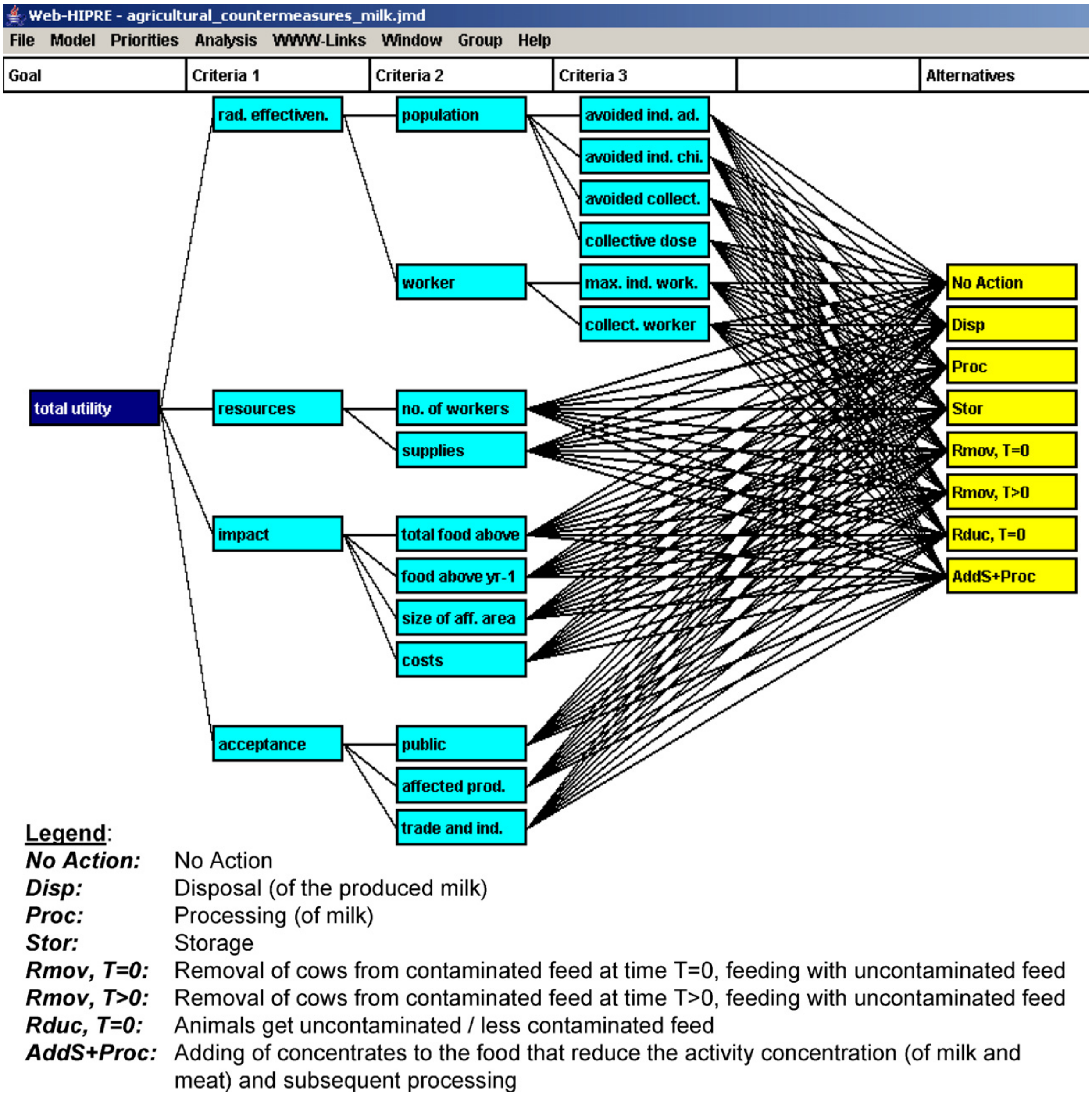


Fig. 3. Attribute tree for the exemplar case study. The abbreviations of the criteria are declared in Table 1.

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

Table 2
Decision table—Part 1–values directly imported from RODOS[a]

	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
No. of 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

[a]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 3
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

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.
- "no. of workers" vs. "supplies":
  The two attributes "no. of 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

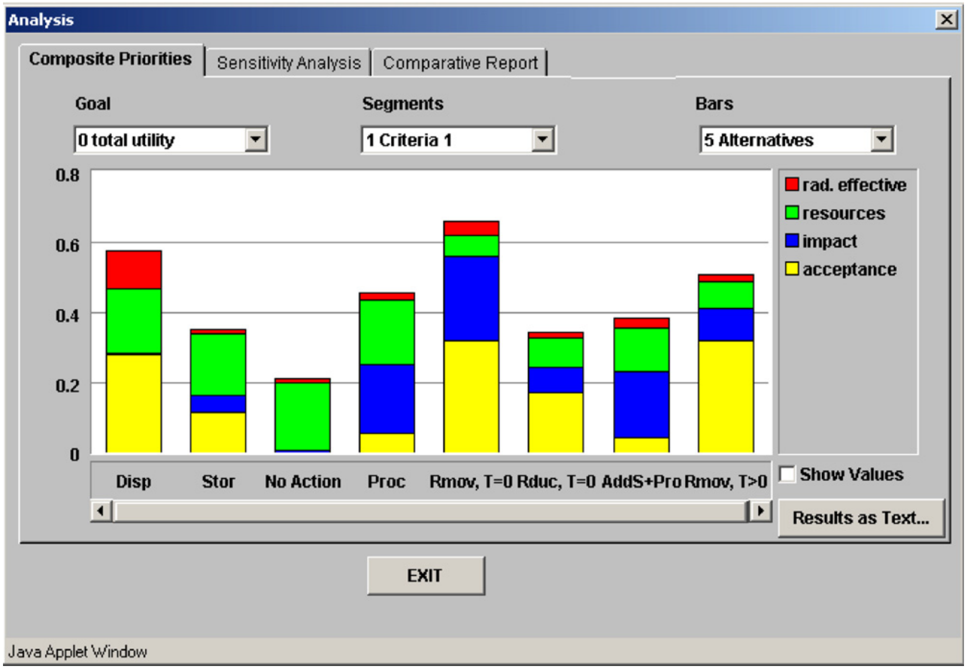


Fig. 4. Results of decision analysis illustrated by Web-HIPRE.

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 shapes were defined for each individual attribute using both linear and exponential functions, as considered appropriate by the participants. After the completion of the preference elicitation the question was raised for discussion 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.

5.4. Selected results

Following the preference elicitation the composite priorities (cf. Fig. 4) were calculated and illustrated by Web-HIPRE. Fig. 4 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 favour "Disp" over "Rmov, $T = 0$", do not have a big effect on the results of the analysis.

In addition, a sensitivity analysis on "acceptance" (cf. Fig. 5) 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.

Finally, the explanation module was used to generate comparative reports as well as sensitivity analysis reports to provide the results of the decision analysis

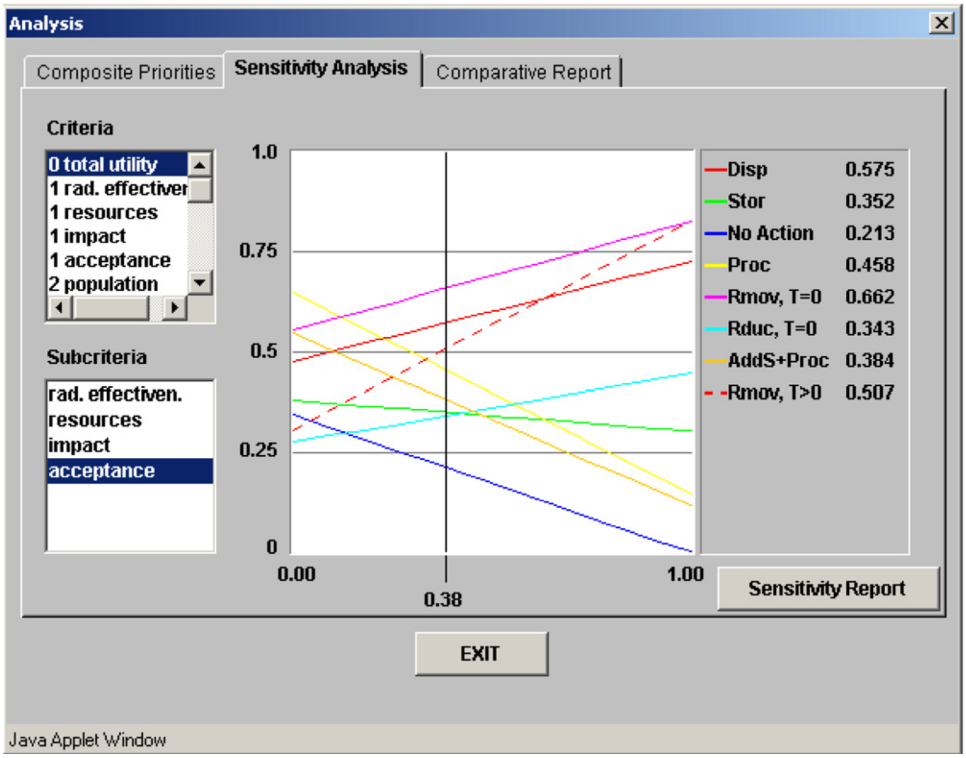
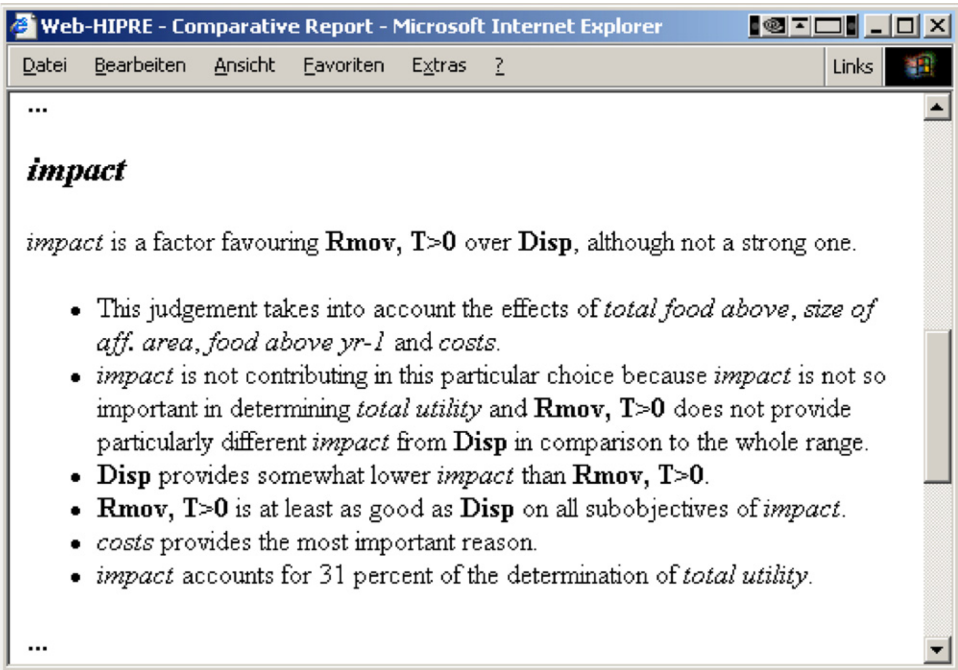


Fig. 5. Sensitivity analysis in Web-HIPRE.



...

impact

impact is a factor favouring **Rmov, T>0** over **Disp**, although not a strong one.

- This judgement takes into account the effects of *total food above*, *size of aff. area*, *food above yr-1* and *costs*.
- *impact* is not contributing in this particular choice because *impact* is not so important in determining *total utility* and **Rmov, T>0** does not provide particularly different *impact* from **Disp** in comparison to the whole range.
- **Disp** provides somewhat lower *impact* than **Rmov, T>0**.
- **Rmov, T>0** is at least as good as **Disp** on all subobjectives of *impact*.
- *costs* provides the most important reason.
- *impact* accounts for 31 percent of the determination of *total utility*.

...

Fig. 6. Extract of a comparative report.

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. Fig. 6 shows the comparison with respect to “impact” (an internal node of the attribute tree).

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. 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.

6. Conclusions

Complex decisions require input from various disciplines and fields of expertise. 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 the (potential) users in practice 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. 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. MCDA 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 DMs 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 [9]. 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, advanced multi-criteria methods taking approaches for uncertainty handling into account are needed (see e.g. [45,46]). When information about the preference parameters is afflicted with uncertainties, missing or only partially available, (parametric) sensitivity analyses are very important [47,48]. While the classical one-dimensional sensitivity analysis, which is offered by Web-HIPRE, allows to assess the robustness of a decision with respect to weight changes, the major drawback of the procedure is that it is limited to varying one weight at a time. Considering the impact of the simultaneous variation of several weights of a decision model by allowing the assignment of weight intervals instead of precise values would not only facilitate the difficult process of weight elicitation but would also contribute to an easier way of achieving consensus in group decision processes (see [49]). Another approach to tackle this problem is the combination of techniques from data envelopment analysis (DEA) with MCDA. Even though these two fields of research have developed almost completely independently for a long time (see e.g. [50,51]), promising approaches that seek to combine elements of both fields have been proposed recently [52,53]. However, 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.

The methods described in this paper are also relevant for researchers and practitioners in other domains. For instance, they are easily extendable to (other) 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. Furthermore, 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 can easily be transferred to other areas being tangent to any of these topics.

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