Preference Elicitation and Sensitivity Analysis in Multi-Criteria Group Decision Support for Nuclear Remediation Management

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ABSTRACT

The resolution of complex decision situations in crisis and remediation management following a man-made or natural emergency usually requires input from different disciplines and fields of expertise. Contributing to transparency and traceability of decisions and taking subjective preferences into account, multi-criteria decision analysis (MCDA) is suitable to involve various stakeholder and expert groups in the decision making process who may have diverse background knowledge and different views, responsibilities and interests.

The focus of this paper is to highlight the role of MCDA in nuclear emergency and remediation management on the basis of a hypothetical case study. Special emphasis is placed on the modelling of the decision makers' preferences. The aim is to explore the sensitivity of decision processes to simultaneous variations of the subjective preference parameters and consequently to contribute to a facilitation of the preference modelling process by comprehensibly visualising and communicating the impact of the preferential uncertainties on the results of the decision analysis.

Keywords

Emergency and Remediation Management, Multi-Criteria Decision Support, Stakeholder Involvement, Group Decision Making, Preference Elicitation, Preferential Uncertainties.

INTRODUCTION

Decision making in emergency management involves many parties with different views, responsibilities and interests, for which a consensus must be found. Multi-criteria decision analysis (MCDA) can be helpful to enhance public confidence and understanding as well as transparency and traceability in relation to such complex group decisions (see Geldermann et al., 2007; Belton and Stewart, 2002; Bose et al., 1997). Additionally, different relevant criteria (e.g. economic, ecological and technical criteria as well as socio-political aspects) can be taken into account. Without such trust building components, decisions might not be accepted by the public and the potential benefit of a decision might double back to negative results (Bertsch et al., 2006c). With the increasing demand of media and the public for information and justification from authorities, methods are required to assess how decisions are taken.

However, a crucial part in any multi-criteria analysis is the modelling of the decision makers' preferences. In multi-attribute value theory (MAVT), preferential information is modelled by weighting factors (i.e. *inter-criteria* comparisons) and value functions (i.e. *intra-criteria* preferences). The uncertainties associated with the determination of these preferential parameters are often underestimated. While methods such as SWING and SMART (see Von Winterfeldt and Edwards, 1986; Edwards, 1977) seek to support decision makers (or their advisers) in eliciting appropriate weights for the different criteria in MAVT by allowing the assignment of weight ratios instead of direct weights, the most difficult problem is often the determination of precise weights or weight ratios. Experiences gained from conducting scenario-focused decision making workshops and also training courses on the use of decision analysis, have shown that decision makers (or their advisers) do in general appreciate the benefits from applying MCDA but that they need more guidance. They were often unsure about an exact quantification of the modelled preferences. Hence, an appropriate handling of the so-called "preferential uncertainties" is of particular importance.

The problem of preferential uncertainties is closely interconnected with the field of group decision processes (see e.g. Zhang, 2004; Salo, 1995). We think that it could be easier (for single decision makers but, in particular, also for groups) to allocate weight ranges (intervals) instead of precise values. Furthermore, it should be noted that preferences may certainly vary according to value systems that are influenced by culture which, in particular, has to be accounted for when decision groups involve persons with different cultural backgrounds. Using approaches for sensitivity analysis that allow to find out whether or not the variation of certain weights has an impact on the ranking of the alternatives, disagreements which do not affect the results can be eliminated from debate and the group can focus on discussing the differences that do matter in terms of the results (Bertsch et al., 2006b; French, 2003).

A series of decision making workshops focusing on the evaluation of countermeasure and remediation strategies with respect to multiple criteria in the event of a nuclear emergency was organised across Europe (see e.g. Geldermann et al., 2007). These workshops were inter alia aimed at familiarising the responsible persons with the MCDA tools and methods and at guaranteeing that the developments meet the requirements of the users. The group of participants included officials and politicians of regional, state and federal authorities as well as expert advisers for radiation protection and a number of stakeholder groups (for more details, see Geldermann et al., 2005). Since the public acceptance of decisions in the late phase is essential for a successful implementation of the remediation strategies, the stakeholders should not only be involved in the decision process but should also be considered as decision makers.

Applying MCDA in the workshops has highlighted the potential of the methods. Furthermore, the workshops were successful in determining issues for further developments of methodology and decision support tools (Raskob et al., 2005). In these workshops, the decision making process and, in particular, the process of preference elicitation was guided by a moderator/facilitator whose responsibility is to lead the discussion and to introduce the individual work steps. Furthermore, moderators steer the group with questions as the work continues and manage the interactions with and between participants. Without actively interfering into the discussion their task is to resolve disagreements and to foster consensus building.

However, in real decision situations, especially in emergency management, it is likely that decision making teams/groups are geographically dispersed. This constitutes a new challenge for the facilitation of preference elicitation processes. Web-based tools such as Web-HIPRE[1], providing a functionality for (distributed) group decision support, can help to overcome this problem. The only drawback is that, so far, this functionality of Web-HIPRE is limited to "standard group decision support". The focus of this paper is the suggestion of a possible extension of this functionality. An approach that allows to explore the impact of simultaneous variations of the subjective preference parameters is proposed. This approach could be combined with the web-based group support function. The aim is to facilitate the process of preference elicitation and to comprehensibly visualise and communicate the impact of the preferential uncertainties on the results of the decision analysis. value

DECISION SUPPORT FOR NUCLEAR EMERGENCY AND REMEDIATION MANAGEMENT

In order to harmonise decision making in the event of a nuclear or radiological emergency in Europe, a common European decision support system was developed – the RODOS[2] system. RODOS provides consistent and comprehensive decision support at all levels ranging from largely descriptive reports, such as maps of the contamination patterns and dose distributions, to a detailed evaluation of the benefits and drawbacks of various countermeasure or remediation strategies and their ranking according to the societal preferences as perceived by the decision makers (Raskob et al., 2005; French et al., 2000; Ehrhardt and Weiss, 2000). The conceptual structure of RODOS includes three subsystems:

- The Analysing Subsystem (ASY) processes incoming data and forecasts the location and quantity of contamination based upon monitoring and meteorological data and models including temporal variation.
- The modules of the Countermeasure Subsystem (CSY) simulate potential countermeasures, check them for feasibility and calculate their consequences.
- Web-HIPRE (see Mustajoki and Hämäläinen, 2000), a tool for MCDA, has recently been integrated into RODOS as Evaluation Subsystem (ESY) to support a team of decision makers in evaluating the overall value of different countermeasure or remediation strategies according to their potential benefits/drawbacks (quantified by the CSY) and preference weights (provided by the decision makers) (Geldermann et al., 2005).

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[1] See e.g. http://www.hipre.hut.fi as well as (Mustajoki and Hämäläinen, 2000)

[2] "Realtime Online Decision Support System for nuclear emergency management", see: http://www.rodos.fzk.de

RODOS is designed to support decision making throughout all phases of emergency management. In the early phase, emergency management involves decisions on measures of disaster response, such as evacuation, sheltering or distribution of stable iodine tablets. In the longer term, more complex decisions on decontamination and remediation strategies, restricted access measures (e.g. relocation) and agricultural countermeasures are required. Many parties with different views, responsibilities and interests are involved and conflicts of objectives need to be resolved (see e.g. Geldermann et al., 2007; Hämäläinen et al., 2000). Priorities must be set and a consensus must be found for the various perspectives of the many stakeholder groups. Both, the early and later phase emergency management are part of the calculations of the CSY. However, due to the higher complexity in the later phase, Web-HIPRE was integrated to support the evaluation of alternative countermeasure and remediation strategies, whose potential benefits and drawbacks are quantified by the CSY (Bertsch et al., 2006c).

One field of research within MCDA, which has proven to suit for application in the late phase of nuclear emergency management (see Geldermann et al., 2007; Hämäläinen et al., 2000; French, 1996), is multi-attribute value theory (MAVT), see (Keeney and Raiffa, 1976) for an overview on MAVT. This is the underlying theory in Web-HIPRE. It provides methods to structure and analyse decision problems by means of attribute trees (cf. Figure 2) and to elicit the relative importance of criteria in such a tree.

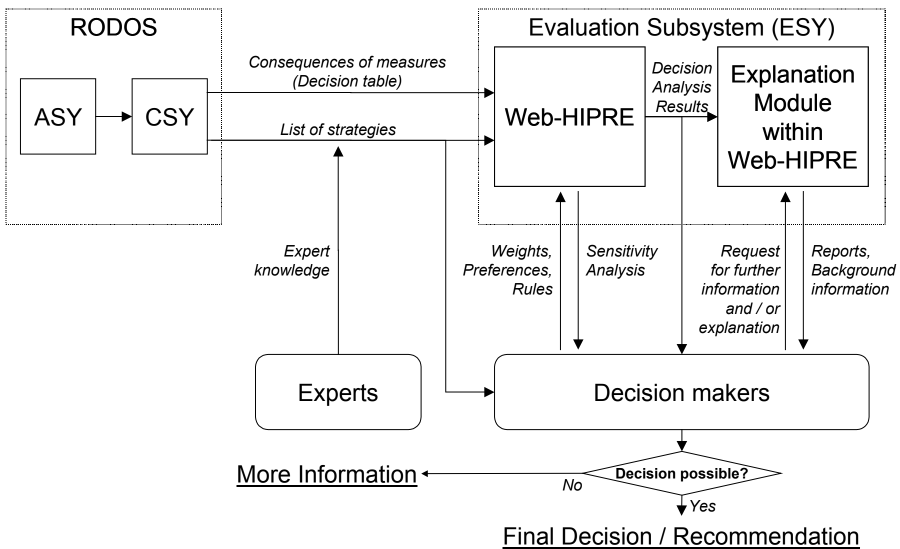

Figure 1: Structure of a decision process supported by RODOS and Web-HIPRE

Figure 1 summarises the preference elicitation and evaluation processes in RODOS and Web-HIPRE. Furthermore, it is indicated in Figure 1 that an ”Explanation Module” has been integrated into Web-HIPRE. This module offers the possibility to generate natural language explanations to enhance the understanding of the evaluation process and therefore seeks to facilitate the communication with the public and the media (Papamichail and French, 2003). It also contributes to forming an audit trail for the decision making process and thus is aimed at improving the acceptability of the system as a whole (Geldermann et al., 2007).

It should be noted that the processes shown in Figure 1 are interactive and iterative. It is possible to correct decision parameters in the case that the decision makers' preferences and value judgments are not accurately represented by the model. In practice however, such an evaluation process is subject to various sources of uncertainty. The occurring uncertainties can be classified in several different ways (see for instance Bertsch et al., 2005; French, 1995; Morgan and Henrion, 1990). According to their respective source, a distinction can be made between “data uncertainties”, “parameter uncertainties” (e.g. uncertainties related to the preference parameters of a MCDA model) and “model uncertainties” (uncertainties resulting from the fact that models are ultimately only simplifications/approximations of reality (see French and Niculae, 2005)). The focus in this paper is on modelling and handling the uncertainties associated with the different preference parameters. In order to explore the impact of simultaneous variations of these subjective parameters, multidimensional sensitivity analyses can provide valuable insights into the decision situation.

A HYPOTHETICAL CASE STUDY

The fictitious nuclear emergency scenario described in this section originally provided the basis for discussion within a moderated decision making workshop in Germany. Details of the case study going beyond the description in this paper as well as the processes of problem structuring and the "conventional" preference elicitation including common sensitivity analyses, as carried out in the workshop, are described in (Geldermann et al., 2005).

Scenario description

The fictitious contamination situation was assumed to be caused by a hypothetical serious accident at a nuclear power plant, which caused an immediate shutdown of the reactor. A few hours after the accident the fictitious release of radioactive material into the atmosphere started and lasted over a period of a few hours. According to initial estimations by plant operators, approximately 50 % of the plant inventory of radioactive noble gases and approximately 0.1 % of the inventory of radioactive iodine and radioactive aerosols were released during the accident. Subsequently, it was assumed that the radioactive cloud was blown over a city of 28 000 inhabitants. Heavy precipitation and thunderstorms resulted in local inhomogeneities of the ground contamination. Furthermore, it was assumed that all necessary immediate and early countermeasures, including early food countermeasures, were taken.

The key phases of MAVT in the case study

Problem structuring, the first step within a MAVT analysis, is concerned with appropriately formulating rather than solving a problem (Belton and Stewart, 2002). It gives a better understanding of both, the problem and the values affecting a decision. It also serves as a basis for further analyses and as a common language for communication (Rosenhead and Mingers, 2001). In addition to identifying and specifying objectives (criteria) and attributes as well as decision alternatives, the aim of problem structuring is the hierarchical modelling of the criteria into an attribute tree. Within the moderated workshop, the city was explicitly divided into zones of different dose levels. The problem structuring process of the case study resulted in an attribute tree showing the overall goal "total utility" (of a measure) as the top criterion which was further split into the criteria "radiological dose", "logistics" and "costs", where radiological dose was split up again into the avoided collective dose ("A.c. dose") and the avoided individual doses ("A.i. dose" / "A.i.d.") in the different considered zones and logistics was subdivided into waste and work effort (cf. Figure 2). The seven considered countermeasure strategies ranged from "No action" (Strategy S1) to "Additional evacuation, removal of bushes and shrubs, lawn mowing and removal of street surfaces" (Strategy S7). The strategies S2-S6 comprise actions on a scale in between these two "extreme" options.

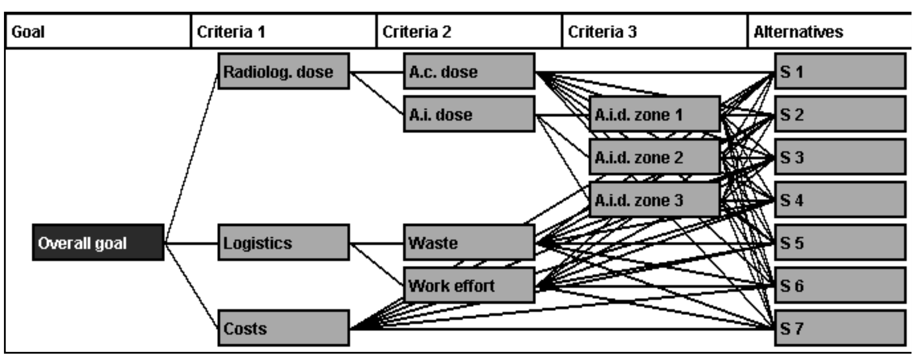

Figure 2: Attribute tree for the hypothetical case study

Subsequently, it is necessary to elicit the relative importance of the criteria in the attribute tree. More generally, a model needs to be constructed that represents the preferences and value judgments of the decision makers. This process is called *preference elicitation*. As indicated already, intra-criteria preferences are modelled by value functions and inter-criteria preferences are modelled by weighting factors in MAVT. The value functions are used to evaluate the strategies relative to the different attributes by mapping their performance with respect to each individual attribute to the interval [0,1] such that the "best" and "worst" possible outcomes correspond to 1 and 0 respectively. As regards the weights of the attributes, it is important to ensure that their sum is equal to one (i.e. they are normed). Various methods exist to support the elicitation of preferences (for an overview see Belton and Stewart, 2002; Pöyhönen et al., 2001; Weber and Borcherding, 1993; Von Winterfeldt and Edwards, 1986).

In the succeeding *aggregation* step within MAVT, a ranking of the alternatives is composed according to the decision analysis. Using a stacked-bar chart (cf. Figure 3), such a ranking does not only illustrate the overall performance score of the considered decision alternatives but also the contributions of the individual criteria.

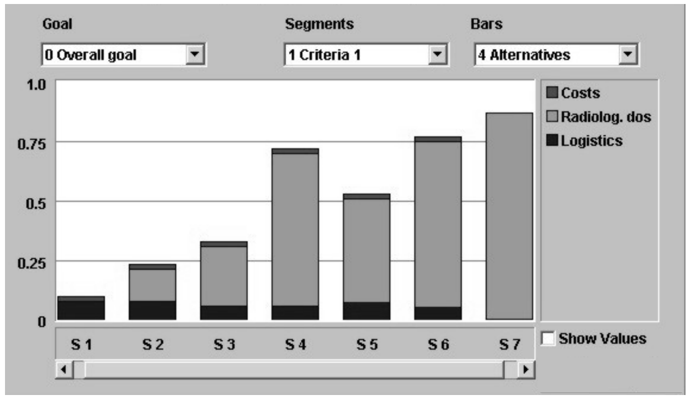

Figure 3: Results of decision analysis illustrated by Web-HIPRE

Besides illustrating the overall performance scores of the considered alternatives, it is important to analyse the robustness of a decision. Allowing an examination of the stability of the results with respect to changes of the weight of a criterion, the lines in the graph of a "classical" *sensitivity analysis*, each associated with one alternative, show the overall performance scores of the (associated) alternatives when the weight of the criterion under consideration is varied from 0 to 1 (cf. Figure 4). If a sensitivity analysis shows that the ranking of alternatives is very sensitive to changes of a weight, the decision makers should carefully check if the weighting accurately reflects their preferences.

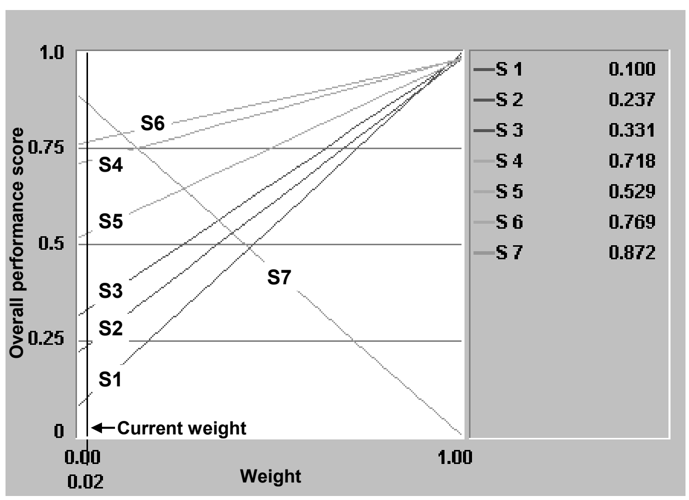

Figure 4: Screenshot of a (one-dimensional) Sensitivity Analysis in Web-HIPRE (on the weight of Costs for the case study)

EXTENDED SENSITIVITY ANALYSES FOR GROUP DECISION SUPPORT

While the feedback from conducting workshops as described in the previous section was very positive in general, the gained experiences have also clearly shown that the participating decision makers (or their potential advisers) need more guidance, especially as regards the elicitation of the preferential parameters. They were often unsure about an exact quantification of their preferences. While the classical one-dimensional sensitivity analysis as offered by Web-HIPRE (cf. Figure 4) can help 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 could not only facilitate the difficult process of weight elicitation but could also contribute to an easier way of achieving consensus in group decision processes. Similarly, investigating the impact of the simultaneous variation of the value functions' shapes can facilitate the process of determining appropriate value functions for each attribute. An approach for both, simultaneously varying the *inter-criteria* preference parameters as well as the *intra-criteria* preference parameters is described in the following. The approach is only described briefly in this paper, formal descriptions can be found in (Bertsch et al., 2006a; Bertsch et al., 2006b). The approach is based on using intervals for the preference parameters instead of precise parameters. Subsequently, since it would be very time-consuming to investigate all reasonable parameter combinations one at a time (see e.g. Butler et al., 1997), Monte Carlo simulation is applied to draw samples within the intervals and to perform a multidimensional sensitivity analysis to explore the effect of the "preferential uncertainties" within the afore assigned intervals.

The problem of preferential uncertainties is not new, it has been addressed by many researchers and practitioners in the field of decision analysis. For instance, (Proll et al., 1993; Rios and French, 1991) propose mathematical programming techniques to explore the sensitivity of multi-criteria decisions when simultaneously varying different decision parameters. In "Preference Programming", the interval judgments within AHP are interpreted as linear constraints and a series of linear programming problems is solved (Salo and Hämäläinen, 1995). (Mustajoki et al., 2005) discuss "interval SMART/SWING", an approach that generalises the SMART and SWING methods by allowing interval judgments for the weight ratios. (Lahdelma and Salminen, 2001) and (Mavrotas and Trifillis, 2006) propose to explore the weight space (i.e. describing the valuations which would make each alternative the most preferred one) when preference information is afflicted with uncertainties, missing or only partially available. The use of simulation techniques for sensitivity analyses has for instance been proposed by (Mateos et al., 2006; Butler et al., 1997).

Inter-criteria preferences

As mentioned already, intervals are used to model the inter-criteria preferences instead of discrete weights (Bertsch et al., 2006b). Thinking about a group of decision makers, the intervals could for instance be obtained by permitting each group member to define his or her weights individually and then defining the intervals as the superset of the individual weights. Alternatively, the group members could be permitted to use intervals, too, and the group interval could be obtained by using the superset of the individual intervals. Then, the uncertainties of the inter-criteria preferences for all attributes can be described by a multi-dimensional interval. When drawing Monte Carlo samples from the multi-dimensional interval it is important to ensure that the drawn weight combinations are "valid", i.e. they fulfil the constraint that the sum of the weights of all attributes is equal to one. Once the samples are drawn, the approach is in principle straightforward and furthermore computationally easily feasible.

Intra-criteria preferences

Since the determination of the value functions' shapes is a difficult task in practice, it can be helpful for a group to investigate the impact of varying the shape(s) of the value function(s) within certain intervals (see also Bertsch et al., 2006a). In comparison to exploring the impact of simultaneously varying the weights, the procedure is much simpler for value functions since there is no constraint such as that their sum needs to be equal to 1 as for the weights. Besides varying the value functions' shapes it is also interesting to investigate the effect of varying their domains' boundaries. In practice, the boundaries are often defined by the minimum and maximum scores actually achieved by the different alternatives (with respect to the considered attributes). By following this approach, theoretically possible better or worse outcomes are neglected. However, the estimation of reasonable values for these theoretically possible boundaries is a difficult task. Thus, in order to support a decision making team in coping with this task, it is suggested to analyse whether or not the variation of the boundaries has an impact on the results. The procedure is very similar to the one described for the value functions' curvatures. In both cases, Monte Carlo Simulation can be used to draw the samples.

Interval preference modelling and selected results

A prototype has been implemented which provides methods, in accordance with the decision makers' requests, to perform preferential sensitivity analyses for one or several preference parameter(s). For the hypothetical case study, the capability of the prototype is demonstrated. A weight interval of either 10 % or 15 % around the discrete weights, which were used in the workshop, is assigned to each attribute (cf. Figure 7 (a)). In addition, the value functions' curvatures and their domains' boundaries are varied.

Results for 1000 samples of preference parameter combinations are shown in Figure 5. Diagram (a) shows the spread of the overall performance scores as a result of the preferential uncertainties. The horizontal bars show the results for the deterministic weights as used in the German decision making workshop. Using intervals for preference modelling, the strategies S7, S6 and S4 are not clearly distinguishable from each other in the case study. But the results in diagram (a) also show that, even in the "worst cases", the strategies S4, S6 and S7 have a higher performance score than the strategies S1, S2 and S3 in the "best cases" which means that the latter options are dominated by the first three.

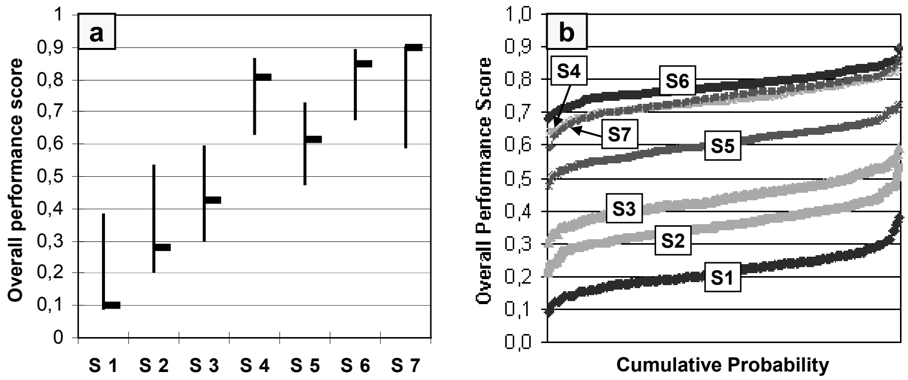

Figure 5: Results for the case study: (left) – overview of the spread of the results; (right) – overall performance scores plotted against the cumulative probability

While diagram (a) provides a good overview on the impact of the uncertainties of the preferential information, it is not possible to read off information about the relative frequency of the performance scores of the different alternatives (i.e. performance scores at the lower and upper bound of the shown ranges will usually occur less frequently than those in the middle of the ranges). However, such information is provided in diagram (b). The illustration by means of plotting the performance scores versus the cumulative probability has also been proposed by (Butler et al., 1997). We favour this visualisation over the often used box plots since more detailed information of the complete distribution of the results is provided.

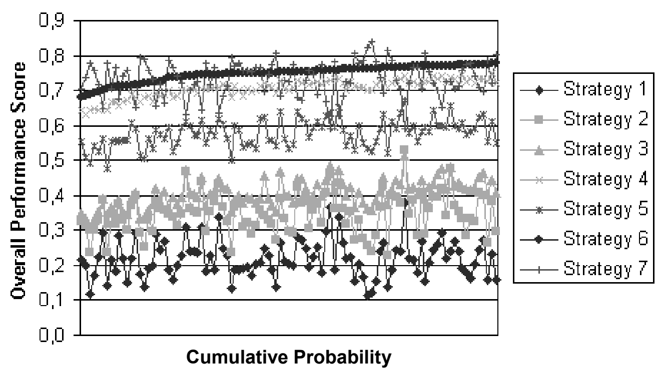

Figure 6: Results: overall performance scores sorted by Strategy S6

It is important to note that the performance scores of the different alternatives at an imaginary "perpendicular cut" through the diagram of the cumulative probabilities (Figure 5 (b)) do not necessarily belong to only one weight combination. Thus, information about the exact percentage at which a certain alternative is ranked first cannot be read off from this diagram immediately. This means, for instance, that it cannot be concluded from Figure 5 (b) that Strategy S6 receives the highest overall performance score for all drawn weight combinations. However, an illustration as in Figure 6 (where S6 is visualised as in Figure 5 (b) but the other strategies are sorted in such a way that their scores at an imaginary "perpendicular cut" do belong to the same weight combination) or an analytical evaluation can be helpful to provide such accurate information. For the considered case study, Strategy S6 is ranked first for 72 % of the drawn weight combinations and Strategy S7 for 28 %. Additionally, a visualisation as in Figure 6 can provide insight into potential correlations between the different strategies. For example, Figure 6 indicates a correlation between the strategies S6 and S4.

Furthermore, a "backwards calculation" can help to investigate the origin of potential differences in the results (cf. Figure 7). In addition to the information provided in Figure 5 and Figure 6 it would be very helpful for a decision making group to explore which preference parameter combinations result in S6 and which combinations results in S7 as the strategy with the highest performance score. For the weights, Figure 7 provides such information in an easily understandable way. Diagram (a) shows all drawn weight combinations. Diagram (b) only shows those weight combinations for which S7 has the highest overall performance score. While the intervals in diagram (a) and (b) seem to be more or less the same for almost all attributes, differences can be detected for the attributes "Waste" and "Costs". While the assigned intervals allow the weights to vary between 0.01 and 0.15, the weights of "Waste" and "Costs" for which S7 turns out to be the most preferred strategy are not higher than 0.1 (indicated by the loops in diagram (b)). Such information can be very valuable for groups so that their discussion can focus on the most important preference parameters in terms of their respective impact on the results.

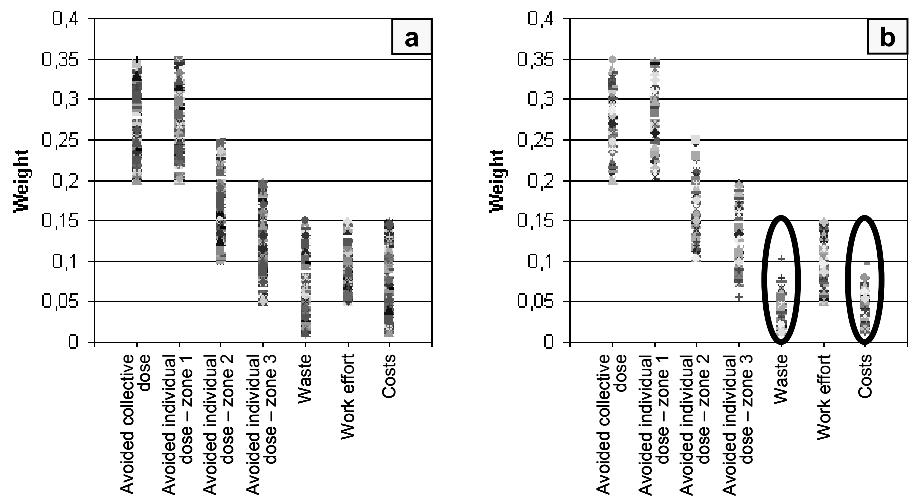

Figure 7: "Backwards calculation": (left) – all drawn weight combinations; (right) – weight combinations for which S7 has the highest overall performance score

The presented sensitivity analysis approaches can contribute to facilitate the consensus building within a group. It is likely that different members of a group argue for different preference parameters. The described methods can provide valuable insights into the robustness of a decision and also allow to explore trade-offs between conflicting objectives (such as "radiological dose" and "logistics"). For instance, the results for the considered case study have shown that in consequence of the high logistic effort and high costs, Strategy S7 is only ranked first if the weights assigned to "Waste" and "Costs" do not exceed 0.1.

CONCLUSIONS

An approach has been introduced to consider the impact of simultaneous variations of several (preferential) parameters on the results of the decision analysis, aiming at facilitating the process of preference elicitation in groups, exploring the robustness of the analysis and allowing an informative overview and deeper insight into the decision situation. It should be emphasised that the approach is aimed at communicating and visualising the uncertainties associated with the results of the decision analysis by explicitly illustrating their spread – i.e. the ranges in which the results can vary. It would now be interesting to test and evaluate the approach in further decision making workshops, possibly also in an e-workshop, in order to ensure that it meets the needs of decision making processes in practice.

The proposed interdisciplinary methods can be enhanced and extended in several ways. For instance, decisions are usually not taken at one single point as it is often assumed for reasons of simplicity. In reality, decisions are rather nested in a series of decisions which are related to each other (French and Rios Insua, 2000). Moreover, up-to-date data – if available – would be included for each new decision (Raskob et al., 2005). Thus, the aim is the development of operationally applicable extensions of the "standard methods" which reflect the sequential and iterative process of decision making in real life. Additionally, in order to increase the usability and acceptance of the more complex approaches that take uncertainties into consideration, it is planned to extend the explanation module (cf. Figure 1) by adding explanations about the uncertainties in the results.

In addition, the approaches can be extended to industrial emergencies where both, an increased awareness of the possibility of technical failure of industrial systems and an improved preparedness to cope with unexpected emergencies (including natural hazards), are desirable since the industrial infrastructure can be severely harmed. Finally, a quantitative analysis of the (economic) impact of the effects of an extreme event on industrial production systems (implicating global, hierarchically structured supply chain networks nowadays) would be worthwhile, including the modelling of cascading effects (e.g. consequential costs) within industrial production as a whole.

ACKNOWLEDGMENTS

This research is closely related to work carried out within the EURANOS project (see http://www.euranos.fzk.de) funded by the European Commission. The authors wish to acknowledge the support by the Commission and all involved project partners.

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