Integrated Environmental Assessment and Management — Volume 17, Number 2—pp. 376–387

Received: 26 February 2020 | Returned for Revision: 18 September 2020 | Accepted: 13 November 2020

Decision Analysis

Facilitating the Decision-Making Process After a Nuclear Accident: Case Studies in the Netherlands and Slovakia

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ABSTRACT

Nuclear accidents do not occur frequently, but their biological, psychosocial, and/or economic consequences may be severe. Hence, a thorough preparation for nuclear emergencies is needed to provide appropriate actions. During the transition phase of an accident, it is vital to include stakeholders in the decision-making process in order to gain support for the recovery strategy to be implemented as well as to share different perspectives, knowledge, and views on the decision problem. Because nuclear accidents are complex, involving many relevant factors that range from technical aspects such as health effects and costs to nontechnical issues such as social acceptance, a multicriteria decision analysis (MCDA) may facilitate the decision-making process. The aim of this study was to investigate the usefulness of MCDA in the transition phase of a nuclear accident. To this end, an MCDA tool, which uses the weighted sum of a set of normalized criteria, was explored in exercises carried out in panel meetings with a selected set of (largely) governmental stakeholders. The panel meetings were performed in the Netherlands and the Slovak Republic. The exercises were based on a fictitious case study that affected the urban environment of a small city. Prior to the meetings, a set of 8 possible recovery strategies was identified. The use of the MCDA tool showed that it facilitated the decision-making process because it allowed for a structured and transparent approach in which stakeholders with diverse backgrounds can express their opinions and perspectives and reach consensus on the most appropriate recovery strategy. As such, it could be applied to a broader field of research involving any chemical release that necessitates an extended recovery strategy. Future research is needed in order to incorporate psychosocial effects of a nuclear accident as well as a broader group of stakeholders in exercises. *Integr Environ Assess Manag* 2021;17:376–387. © 2020 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

Keywords: Nuclear accident   Recovery   Decision-making process   MCDA

INTRODUCTION

The likelihood of a nuclear accident is low, but its consequences can be severe. The Chernobyl, Ukraine, and Fukushima, Japan, accidents in 1986 and 2011 had major long-term impacts on the living environment of the local populations. Elevated dose rates and radionuclide concentrations around the accident sites prevented the return of the local population to their original living environments because there was no implementation of an extensive urban decontamination and radiation protection program (Gray et al. 2002; IAEA 2015).

In order to protect human health after a nuclear accident, it is crucial to take appropriate actions that aim to minimize human exposure and to protect the living environment (Lindell 2000). Actions are needed during the different stages of a nuclear accident. In the emergency phase, appropriate protective and response actions are needed to protect human health, for example, by relocating people. The urgent emergency phase, starting directly after the nuclear accident, may last up to several weeks following the accident. Once the external radiation and inhalation of radioactive material from the cloud and also the deposition processes are over or no longer relevant in the area under consideration, the transition phase commences, which may last from weeks to months to years. Whereas the primary objective of the emergency phase is to protect human health, the transition phase focuses on the detailed

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Published 23 November 2020 on wileyonlinelibrary.com/journal/ieam.

evaluation of the radiological situation in the contaminated areas and on the preparation of plans for the recovery to resume social and economic activities (IAEA 2018). Since the Chernobyl accident, national governments have established response plans in order to take appropriate actions upon a nuclear accident, supported by the expertise of the International Atomic Energy Agency (IAEA). These response plans focus primarily on the emergency phase. However, the Basic Safety Standard (EU 2014) indicates that response plans should also include provisions for the transition from an emergency phase to a phase of recovery and remediation. Furthermore, this directive states that stakeholders are to be consulted on the implementation of remediation strategies. The directive, however, does not specify how stakeholders should be involved or how the decision-making process should be established. Therefore, it is up to governmental bodies to implement this directive into their national response plans.

The transition phase, which is the focus of the present study, is complex and involves various criteria and different forms of data and information. Furthermore, objectives may be conflicting between stakeholders. Under such circumstances, it is difficult to take informed, thoughtful decisions (Kiker et al. 2005). Therefore, a structured and preferably transparent approach is needed to ensure that all relevant factors are included and to allow for constructive discussions among the stakeholders involved. Initially, cost–benefit analyses have been proposed in radiation protection responses (ICRP 1983). However, the Chernobyl accident showed that these analyses were not appropriate to handle such a complex situation (Papamichail and French 2012). Because individuals are not well equipped to integrate and process multiple information sources, a multicriteria decision analysis (MCDA) may help in the decision-making process because it aggregates information systematically and facilitates negotiations between stakeholders with conflicting interests (Kiker et al. 2005; Papamichail and French 2012). Within an MCDA, various alternatives are compared, based on a set of predefined criteria and their weights that amount to an integrated outcome. Criteria included can be objective (such as costs) or subjective (such as social acceptance) (Wang et al. 2009; Papamichail and French 2012). Multicriteria decision analysis has been applied in a wide range of fields and has been shown to be particularly useful in complex decision-making processes such as environmental issues with conflicting interests (Gamper and Turcanu 2007; Yang et al. 2012). An overview of the application of MCDA in nuclear response planning showed that MCDA is useful primarily for the transition phase, where there is sufficient time to draft alternative strategies and to identify relevant criteria to include in the decision making (Papamichail and French 2012).

In managing nuclear emergencies, an online decision support system, JRodos (KIT 2017), evolved from Real-time On-line DecisOn Support (RODOS), is used to support decision makers (Geldermann et al. 2009; Papamichail and French 2012). This system originally contained an MCDA tool called WEB-HIPRE, which was tested in a range of workshops across Europe (Mustonen 2005; Geldermann et al. 2009). These workshops confirmed the usefulness of MCDA as a framework for a structured and transparent decision-making process that enables discussions among stakeholders with diverse backgrounds (Geldermann et al. 2009). However, the exploration in the workshops also showed that there is a need to include uncertainties in the input data and in the parameters included in the MCDA tool (Geldermann et al. 2009; Bohunova et al. 2016). Nuclear accidents such as in Chernobyl and Fukushima are subject to a range of uncertainties (French et al. 2017). Uncertainties may include judgmental uncertainties, social and ethical uncertainties, as well as model and computational uncertainties (French 1995). So far, these uncertainties have been addressed through informal discussions and have not been implemented in decision support tools such as JRodos (French et al. 2017). Therefore, there was a need to include uncertainties in the decision support tools used in case of a nuclear accident and to provide possibilities for visualizing and communicating the uncertainty-based outcome to the decision makers. For this purpose, Müller et al. (2020) improved the MCDA tool, which replaced WEB-HIPRE in JRodos.

The aim of the present research was to test the usefulness of the improved MCDA tool in the decision-making process during the transition phase of a nuclear accident. Because current nuclear response plans focus primarily on the emergency phase of a nuclear accident, the outcome of the present study can provide substantial guidance in setting up appropriate nuclear response planning procedures for the transition phase of a nuclear accident.

MATERIALS AND METHODS

Panel meetings

In order to test the improved MCDA tool, panel meetings were organized in the Netherlands and Slovakia. In both countries, 2 meetings were organized (June and November in the Netherlands, February and December in Slovakia). The aim of the first meeting was to bring the participants, who came from different fields with different backgrounds of emergency management, onto the same level and understanding of nuclear accidents. Furthermore, in this meeting, the ideas of experts and stakeholders were collected on criteria and issues that are relevant to establishing a recovery strategy in the transition phase of a nuclear accident. The outcome of this meeting was used as input to the second panel meeting. The aim of this second meeting was to provide the improved MCDA tool to a range of stakeholders and collect their feedback. An open, facilitated discussion was organized to select and prioritize stakeholder preferences on criteria that should be incorporated in the MCDA tool. The stakeholders discussed possible issues with urban decontamination as well as the impact of relocating people.

The decision-making process after a nuclear accident should involve a broad range of stakeholders with diverse backgrounds, preferably including national and local governmental bodies, radiological experts, and nongovernmental organizations (NGOs). However, because it is difficult to involve NGOs in the topic of nuclear accidents, it was decided, for this first testing of the MCDA tool, to invite experts who represent societal concerns. For the Dutch panel meetings, relevant stakeholders were identified by the project team and invited to the meetings. A previously established national panel was used for the Slovak panel meetings. Stakeholders were invited via email that provided the aim and program of the meeting. Several reminders were sent to maximize the number of participants. The first panel meeting in the Netherlands consisted of 18 members and the second meeting of 12 members. Participants represented Dutch ministries involved in emergency response after a nuclear incident, 2 local safety regions in the Netherlands responsible for crisis management, and the Authority for Nuclear Safety and Radiation Protection (ANVS). Furthermore, social scientists representing citizens' views as well as experts on radionuclides and nuclear accidents from universities and research institutes were present. The first panel meeting in the Slovak Republic was conducted in the form of a seminar and consisted of 19 members. The second meeting consisted of the same number of stakeholders and was composed of the usual decision-makers involved at different levels of the emergency preparedness, response, and recovery management activities. The participants represented the Nuclear Regulatory Authority and Public Health Authority, the ministries and national administrations concerned by postaccident issues, public and private expert institutes and universities in the field of nuclear safety and radiation protection, regional civil protection and crisis management offices, mayors of villages, and representatives of the municipality crisis staff.

In both meetings, a facilitator guided the discussions. In the Netherlands, the facilitator of the first meeting was an expert in crisis management. The facilitator in the second meeting had a background in costs of illness and had expertise in guiding group discussions. For the Slovakian panels, the facilitator was an experienced trained researcher with expertise in leading panel meetings and scenario-based workshops. The use of a facilitator allowed the other participants to concentrate on the content of the meeting. Both meetings started with introductory presentations, after which the group was split in two to enable a more thorough discussion of the topics. The group was split such that both had a comparable composition. The outcome of the discussions was shared with the whole group during the plenary sessions that followed.

Case study

Fictitious accidents were used as input to the panel discussions. For the Netherlands, the fictitious accident was set at the nuclear power plant (NPP) of Borssele, resulting in a contamination of the “Noordoostpolder” in the Netherlands. The case study focused on the urban environment of the city Emmeloord (~25 000 inhabitants, built-up area ~6 km^2) situated in the Noordoostpolder (see Figure 1A). The fictitious nuclear accident in Slovakia took place in the Bohunice NPP with an external release of radioactivity to the environment that resulted in a contamination of the territory given in Figure 1B. The Piestany municipality, which is a spa town within the Trnava region, was the main area for the discussions. The Piestany population reflected about 28 000 citizens and an additional 6000 spa guests. The area of municipality is about 44 km^2 with 24% of built-up area (~11 km^2). It was assumed that the panel was gathered for a discussion 3 d after the accident. As input to the discussions, aspects and information about the daily life issues and plans, including traditional events in Piestany during the summer period, 3 mo after the accident, were prepared in advance.

A set of possible recovery strategies was drafted based on the guidance book from Nisbet et al. (2017) prior to the meetings:

1) Do nothing: No recovery options implemented.
2) Grass/Roads: Grass is cut and grass clippings removed; roads are vacuum cleaned to remove contaminated dust.
3) Low waste 1: Roofs are cleaned, the interior of houses is vacuum cleaned, grass is cut and waste is removed, and trees and plants are removed.
4) Low waste 2: Same as low waste 1 with an additional rotovation of soil, grass, and plants.
5) High waste: Roofs are replaced, the interior of houses is vacuum cleaned, and soil, grass, trees, and plants in the area are removed.

Recovery strategies 3 to 5 could also be combined with a 2-mo relocation period, increasing the number of strategies to 8. The consequences for health, costs, and waste for each of the recovery options were evaluated using the European Model for Inhabited Areas (ERMIN2) (Charnock et al. 2009, 2016). The ERMIN2 model is a tool for the analysis of recovery strategies for contaminated environments. The tool calculates dose reduction factors, the amount of radioactive waste, the amount of work for the implementation, the collective dose received by workers, and the costs of all recovery options for a specific recovery strategy. The output of the model, that is, health effects, waste amount, and implementation costs for the different recovery strategies (strategies 1–8), was used as input to the panel discussions.

Multicriteria decision analysis tool

Multicriteria decision analysis involved the use of a decision support method to establish a ranking on a set of alternatives, in the given case study of recovery strategies, by providing a comparable value $S_1, \ldots, S_n$ for each strategy through integrating a set of predefined criteria $C_1, \ldots, C_m$. Given that the criteria values usually are of different units and their values might differ in magnitude, the values need to be normalized before integration to provide a comparable reference frame. Normalization is achieved by criteria-specific normalization functions $N_1, \ldots, N_m$. There are several normalization functions, such as min–max normalization, which all have their pros and cons (see, e.g., Belton and Stewart 2002). Furthermore, the criteria may be of different importance when considered, which is reflected in specific normalized weights $w_1, \ldots, w_m$, meaning that in this case they represent trade-offs between (normalized) criteria scores. All this information is integrated in a ranking value by an aggregation method. One of the most popular aggregation methods is the computation of the weighted sum (Papamichail and French 2012), which for each recovery strategy requires the following computation:

$$S_i = \sum_{k=1}^{m} w_k \cdot N_k(C_{k,i}) \quad \forall\ i \in n.$$

The results are sorted accordingly. The strategy having the highest value is assumed to be the most preferable one.

The Karlsruhe Institute of Technology (KIT) in Germany implemented the weighted sum MCDA method as a freely available software tool (https://portal.iket.kit.edu/projects/MCDA/). In addition to the implementation of the method, given that MCDA is a very interactive process, the tool also provides a comprehensive graphical user interface to define and enter values for alternatives and criteria and to interactively manipulate weights. Furthermore, the specifications and results of the MCDA are communicated to the users in various ways, for example, as charts, as textual reports, as well as graphical analyses of correlation and stability. Because values can be affected by uncertainty, the tool also provides means to analyze probabilistic input values by ensemble evaluation and to display the results accordingly (Müller et al. 2020).

The software tool was used in cooperation with and guidance from the stakeholders to rank and evaluate the different recovery strategies of the case study. Criteria to be included in the MCDA were identified in the panel meetings. Prior to the second meeting, objective criteria such as costs and health were defined by the project team and implemented in the MCDA for all 8 recovery strategies, assuming normal distributions. The costs attributing to the criteria consisted of the costs for health treatment, relocation, cleanup, waste disposal, and storage for 50 y. The health criterion consisted of the number of predicted fatal cancers over a period of 50 y after the accident. Apart from objective criteria, subjective criteria also were selected in the panel meetings. In the Dutch panel meeting, it was decided to quantify values for these subjective criteria individually by the group members via Mentimeter (www.mentimeter.nl) into a score from 0 to 10. The first criterion scored in this way showed that both the scores and the recovery strategies were not completely clear to all participants. A further explanation clarified both, allowing for a scoring by the participants based on the same underlying principles. In the Slovakian panel meeting, scores for the subjective criteria for all the strategies were assigned as a result of group discussions. In both panels, the relative contribution of the criteria scores to the overall goal of the MCDA was described by normalized linear functions. These functions were obtained using the min and

A

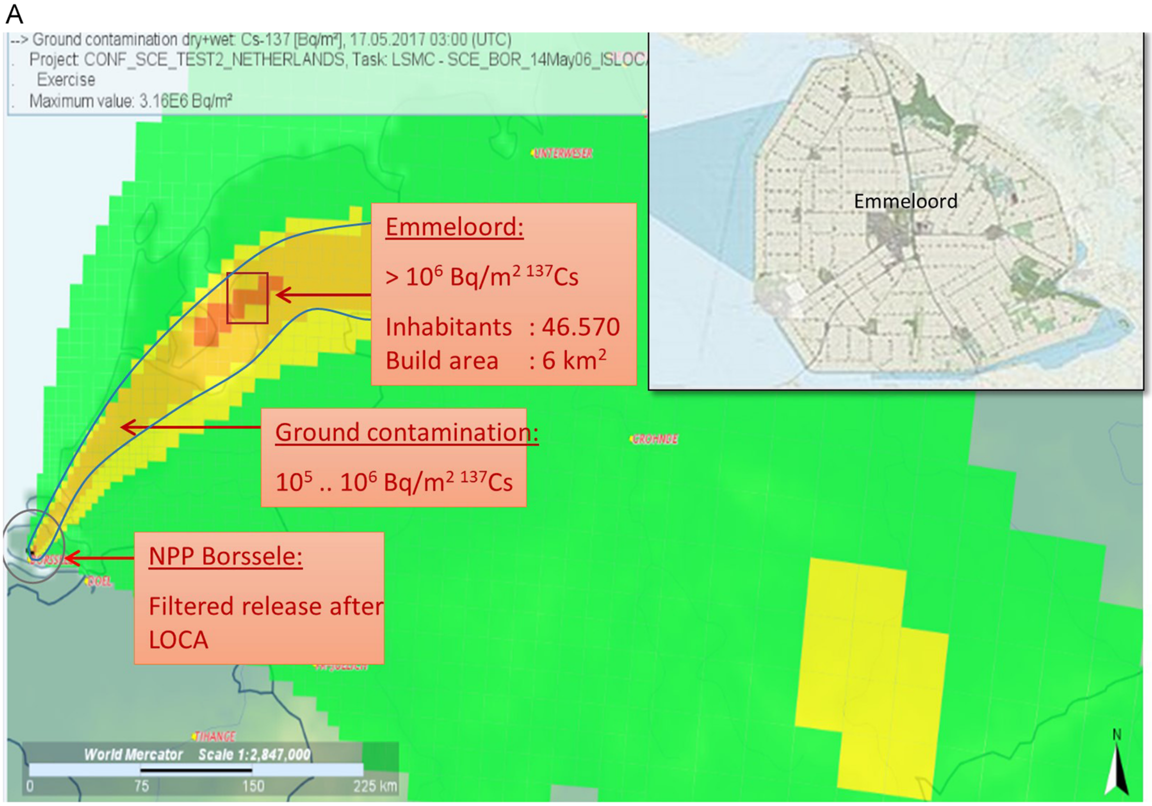

Figure 1. Fictitious accidents in the NPP of Borssele showing ground contamination for ^{137}Cs (Bq/m^2) in agricultural and urban areas of the "Noordoostpolder" in the Netherlands (A) and Bohunice (release: June 3 at 12:00) ground contamination (dry + wet) for ^{137}Cs (Bq/m^2) at ~3 d after start of release (B). NPP = nuclear power plant.

 DOI: 10.1002/ieam.4375

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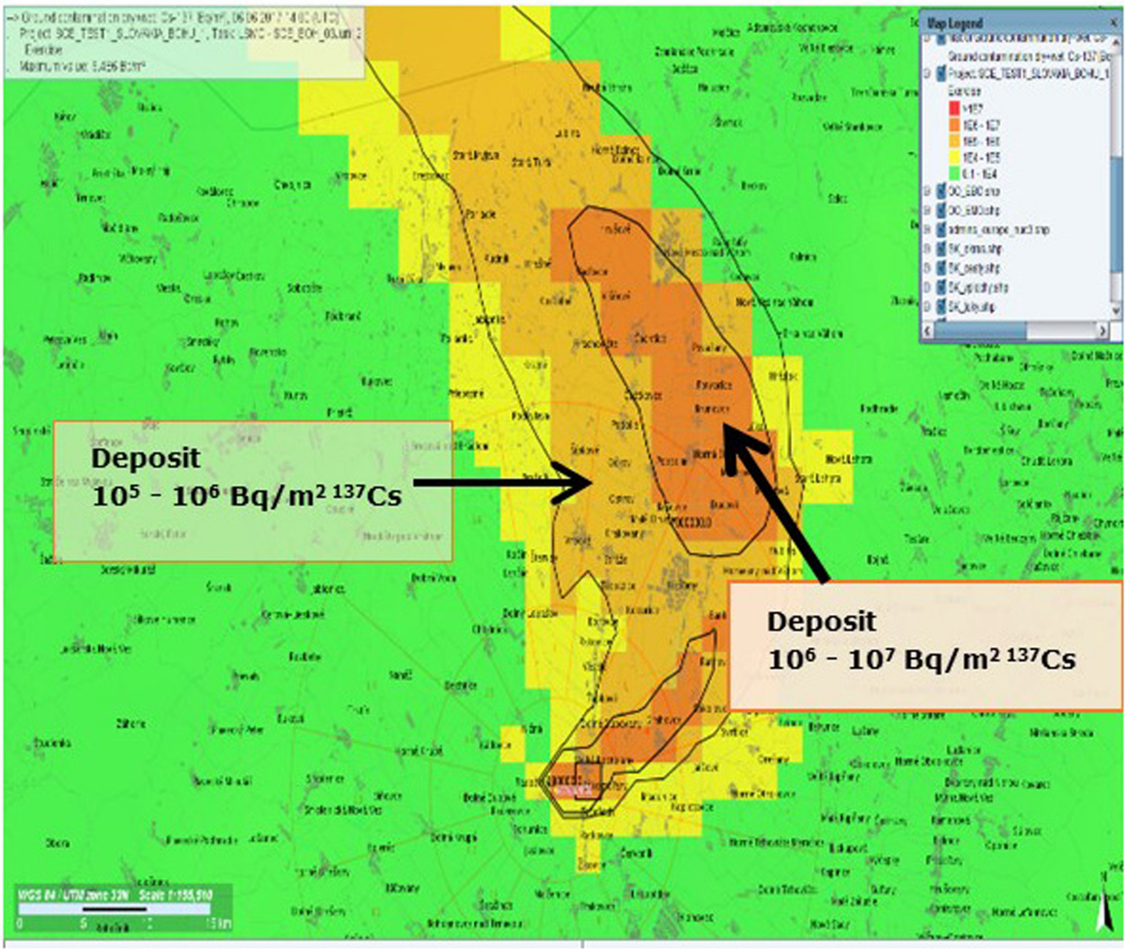

Figure 1. Continued.

max scores corresponding to the lowest and highest scores of alternatives considered in the exercise.

RESULTS AND DISCUSSION

First panel meeting

The use of case studies allowed thorough discussions of the aim of the restoration plan, recovery options, and key criteria for selecting strategies as well as uncertainties encountered in these issues. According to the Dutch and Slovakian stakeholders in the first panel meeting, the specific aim of the recovery strategy is to return to acceptable living conditions as soon as possible. They indicated that normal living in the contaminated territory will be highly disrupted in the emergency phase, and the population will become critical of the government.

The stakeholder discussion in Slovakia focused on possible actions in the fictitious accident and on evaluating the effect of decisions on achieving acceptable living conditions. The discussions incorporated the inherent uncertainties that are associated with the consequences of the contamination scenario, the recovery strategies that may be implemented, and the potential socioeconomic impacts on the affected population. The Slovakian panel was concerned mainly about the availability of trained professionals at national, regional, and local levels, and on whether enough technical resources are available, especially for radiological monitoring. Another concern was the availability of a national emergency plan in which the competences and responsibilities of stakeholders are specified, along with reference levels and other criteria for preparing, implementing, and withdrawing countermeasures. It is important to be well prepared. Furthermore, the panel members stressed that advising the public and stakeholders is relevant. They indicated that urgent protective measures in the emergency phase may influence the development of subsequent countermeasures during the transition phase. Information given to the general public is essential during the distribution of iodine tablets in the emergency phase as well as in the preparedness phase during their predistribution and the campaign to exchange iodine tablets after their expiration period. Communication is, thus, a relevant aspect to ascertain that the population is taken seriously and that the government is taking appropriate actions to protect them. This factor was acknowledged by the Dutch panel members. Additionally, they indicated that uniform decisions should be taken nationally, but flexibility is needed at the local level so that countermeasures correspond to the specific demands of their region.

Selection and quantification of criteria

Several criteria need to be considered in order to build a recovery strategy for the transition phase. Criteria mentioned in the discussion in the Netherlands and Slovakia were public health (radiation related and psychological consequences), economic aspects (direct costs of the recovery strategy, health costs, compensation costs, etc.), feasibility of the recovery strategy (i.e., personal resources expressed by "How difficult it is to allocate the workers?" and technical resources needed), waste storage issues, social acceptance, and willingness to cooperate. Additionally, the Dutch participants mentioned other factors influencing decisions, such as the prevention of fear and social unrest, the ability to cope with the situation, risk perceptions, communication strategies, the continuation of a functioning society, ethical aspects (e.g., justice), international arrangements, and consumer or citizen trust. In Slovakia, panel members indicated that political decisions, the governmental role, education and competence, and the infrastructure are also relevant criteria for selecting a recovery strategy.

Although the MCDA method itself is straightforward, the challenge in a group of decision makers when applying an MCDA lies in general in selecting the appropriate criteria set and in agreeing on the trade-offs, respectively the weights of these criteria. Because clarity suffers from including too many criteria in the MCDA, the participants needed to select the most relevant criteria. Criteria were selected such that they were objective and quantifiable as well as that there were no obvious correlations between any of them. After a group discussion, both national panels agreed to include the following key criteria in the MCDA:

- Public health (health effects). In this exercise, the criterion was expressed as the number of predicted fatal cancers over a period of 50 y after the accident.
- Costs (economical effect). In this exercise, the criterion was expressed as a sum of costs on accommodation during relocation, compensation of productivity losses during relocation, implementing cleanup strategies, waste transport and storage, and cancer treatments for a period of 50 y.
- Feasibility. The Slovakian panel focused specifically on personal resources expressed by "How difficult it is to allocate the workers?" for the implementation of a particular recovery strategy. The Dutch panel had a broader definition. Apart from worker availability, technical (such as material needed) and logistical problems associated with the recovery strategy were also included.
- Social acceptance or willingness to cooperate in the realization of the recovery strategies. This criterion was defined as the public perception toward the recovery, that is, the likeliness the public will agree with the strategy proposed.

The latter 2 criteria, that is, feasibility and social acceptance or willingness to cooperate are much more difficult to quantify because they depend on a subjective assessment. In the Dutch panel meeting, these subjective criteria were quantified individually by the group members via Mentimeter (www.mentimeter.nl) into a score from 0 to 10. The first criterion scored in this way showed that the meaning of both the scores and the recovery strategies were not completely understood by all participants. A further explanation clarified the meaning, allowing for a scoring by the participants based on the same underlying principles. Figure 2 provides an example of the outcome of the scoring method for feasibility of the recovery strategies. This scoring method allowed participants to distinguish the best and worst strategy related to 1 single criterion as well as the consensus range between stakeholders. The Slovakian panel used group discussions to score the subjective criteria. The advantage of such discussions is that stakeholders with different backgrounds, competencies, and knowledge, which have to work together in order to identify the most optimal recovery strategies, can openly express their views and transparently elicit the best possible solutions.

In addition to the 4 most relevant criteria listed above, the Dutch panel identified "administrative dilemmas" (decisions should be in line with the legal framework or international guidelines, and with the communication strategy and should not negatively affect the [inter]national reputation or societal stability), and "quality of life" (a healthy living environment) as key indicators. Both criteria were scored using Mentimeter. The Slovakian panel identified "wastes," expressed by the amount of waste in kilograms, as a key criterion to include in the MCDA tool.

Panel members indicated that in order to gain social acceptance, it is relevant to indicate what specific activities will be performed in the recovery strategy, and why.

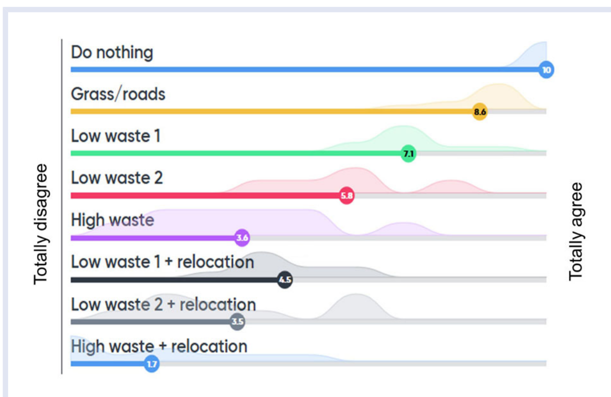

Figure 2. Average scores on a scale from 0 to 10 for the proposition "This clean-up strategy is easily feasible," ranging from "Totally disagree" (score of 0) to "Totally agree" (score of 10). The soft continuous curves represent the variability in the individual answers from the panel members.

 DOI: 10.1002/ieam.4375

Recovery strategies with relocation scored less for the criterion on administrative dilemmas because the panel members indicated that relocation is difficult to explain to the public. Very solid arguments are needed to relocate a whole town. The Dutch stakeholders indicated that the criterion quality of life was difficult to score because the recovery strategies do improve the living conditions, but none of them will result in a high quality of life.

Testing the MCDA tool

The obtained scores and the quantified values for all criteria were included in the MCDA tool (see Figures 3 and 4 for the Dutch and Slovakian panels, respectively) in order to compare the 8 recovery strategies. It should be mentioned that the values used to quantify the criteria are estimations based on assumptions, for example, on evaluating the costs. The aim was to test the usefulness of the MCDA tool in the decision-making process, not to identify the optimal strategy for the identified case study. In the transition phase, stakeholders can contribute to defining the criteria as well as giving input to the recovery strategies to be compared in an MCDA. In our panel meetings, direct weighting was applied for the sake of simplification and speeding up the discussion instead of, for example, Analytical Hierarchy Process (AHP) or swing weighting to determine weight values. The most acceptable strategy obtains the highest outcome; the least acceptable strategy, the lowest outcome (see Figures 5 and 6 for the Dutch and Slovakian panels, respectively). The results were first presented to the Dutch panel without regarding weights, that is, equal weights were used for all criteria. This showed the 2 low waste strategies scored best (Figure 5A). After the results of equal weighting were shown, the stakeholders discussed the weights of the various criteria, which were subsequently adjusted in the MCDA tool. The Dutch stakeholders indicated that health and social acceptance are more relevant than the other criteria, and the weighting was adjusted accordingly (using a 3 times higher weight for health and social acceptance). This

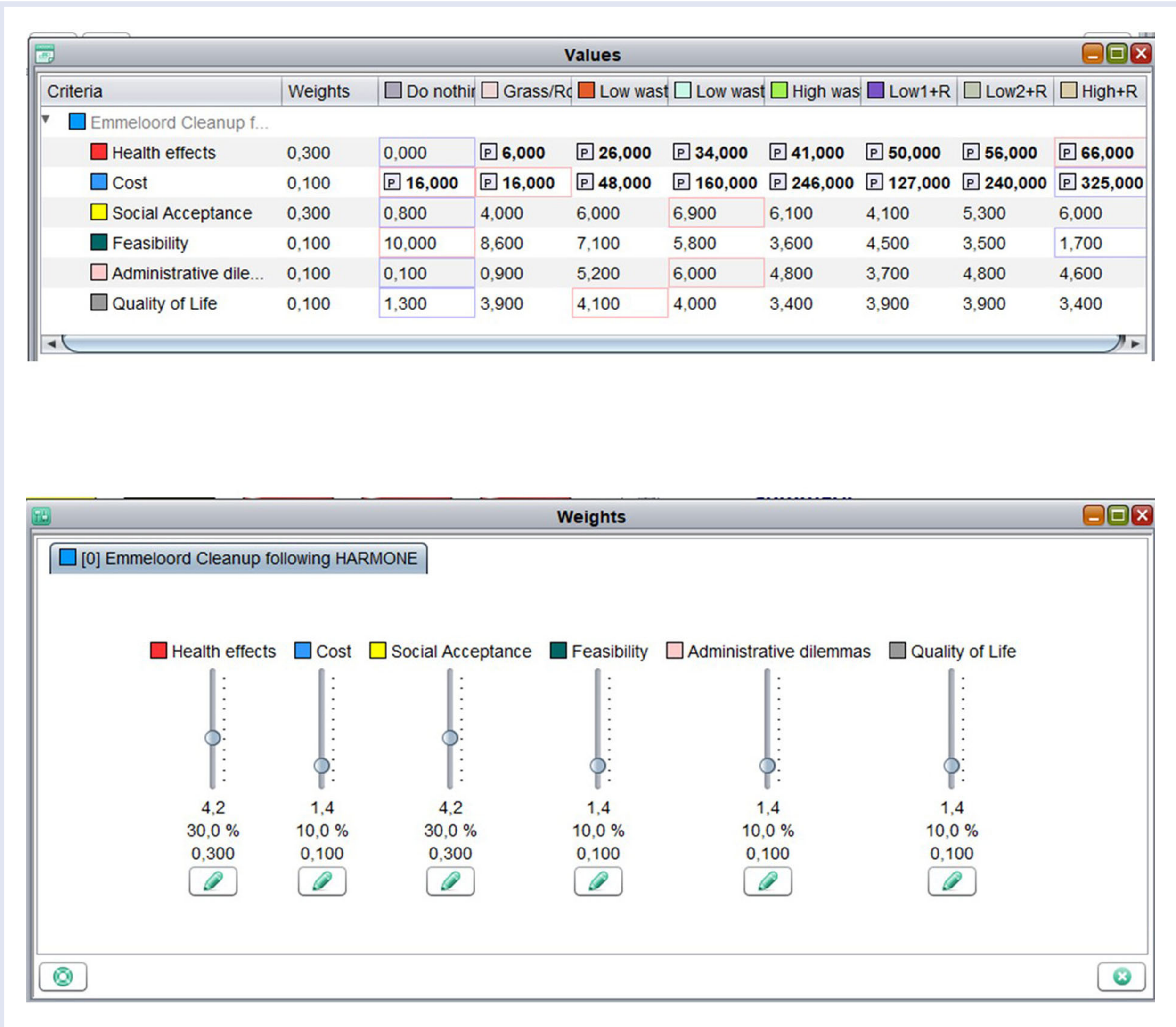

Figure 3. Values and weights of the criteria used for the 8 recovery strategies in the MCDA tool for the Dutch panel. HARMONE recovery strategies were obtained from EU-project HARMONE as indicated in Nisbet et al. (2017). MCDA = multicriteria decision analysis.

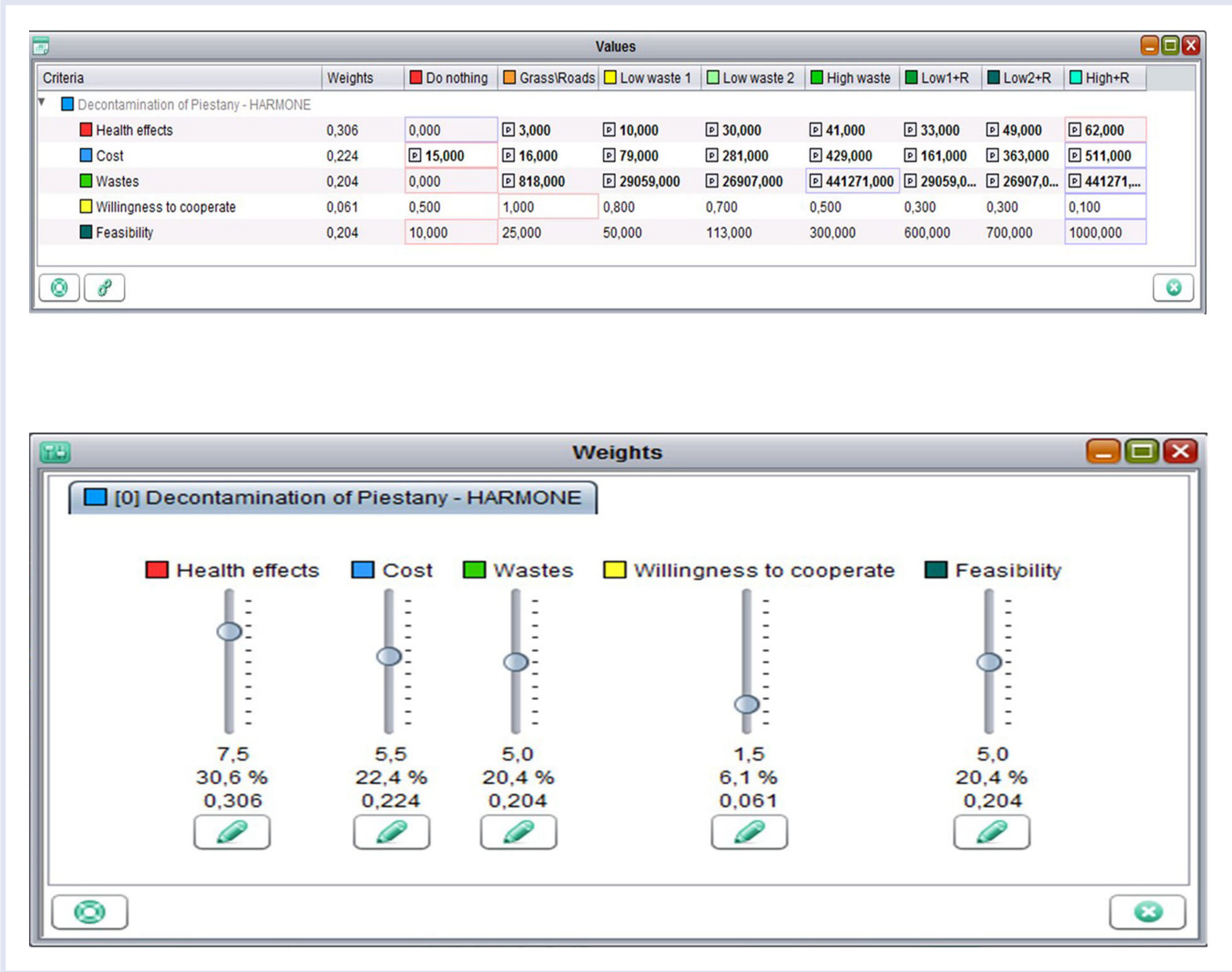

Figure 4. Values and weights of the criteria used for the 8 recovery strategies in the MCDA tool for the Slovakian panel for the Piestany municipality in Slovakia. HARMONE recovery strategies were obtained from EU-project HARMONE as indicated in Nisbet et al. (2017). MCDA = multicriteria decision analysis.

increased the ranking of the recovery strategies with relocation, although the 2 low waste strategies still maintained the highest score (Figure 5B). In the Slovakian panel, the first 4 strategies gave comparable results (Figure 6). Differences in outcomes between the panels (Figures 5 and 6) can be attributed to different value settings and different weighting given to the criteria between the 2 countries. Both panels indicated that weighting is very subjective and should be evaluated carefully. In practice, the weighting should be performed by the governmental bodies at the time of the accident. The MCDA tool provides an interface for this purpose, which allows for following the effect of the weights on the overall ranking of specific strategies and their preferences (Figures 3 and 4). After the panel meetings, a further analysis of the criterion weights was performed by adjusting the weights one at a time. The results showed that, in almost all cases, the high waste strategy and the strategy with no countermeasures are not favored. Only when health is seen as most relevant (with a relative weight of 50%, whereas the other criteria are each set to 10%), the high waste strategies become optimal. The first strategy (do nothing) will not become the optimal strategy because, although the scores for costs and feasibility are high for this strategy, the scores for the remaining criteria are low, resulting in other more favorable strategies. A sensitivity analysis in which all criteria values were increased with 100% at a time (the weights were unchanged) showed that the model outcomes did not differ much, indicating a robust analysis. Future research could focus on including uncertainty in the weights by using techniques such as bootstrapping.

Besides a graphical representation of the outcome of the MCDA, the developed software tool also provides a narrative report, which facilitates the communication on the outcome of the analysis with the stakeholders involved. The narrative report gives a summary of the output, for example, "Low waste 1 is the best alternative, but not with a large margin" and "no criterion is dominating the solution." Furthermore, it indicates the correlations found between criteria as well as the distributions used (e.g., normal distribution with mean and standard deviation). In both panels, health effects and costs were found to be correlated. This correlation seems logical because an increase in countermeasures will have a positive effect on human health but will also be costlier. Furthermore, feasibility was inversely correlated to health effects and costs. Those strategies that are easy to apply (do nothing or low waste options) will not result in high health effects or costs.

At the end of the panel meeting, the usefulness of the adapted MCDA tool was discussed with the participants. The panel members indicated that the current MCDA tool provided a modern state-of-the-art user interface, including various ways to visualize the data and results, which is especially useful when communicating to the stakeholders. The adapted tool was, therefore, preferred over the previously developed WEB-HIPRE. Furthermore, the project team noted several benefits of the MCDA tool during the exercise. First of all, the use of MCDA initiated a discussion on the definitions of the criteria used, which is vital for the successful application of an MCDA. The criteria to be used in the MCDA were, thus, thoroughly discussed to ensure that the stakeholders involved had a common understanding of the terms used.

Secondly, the MCDA tool allows for inclusion of uncertainties in the selected criteria using distribution functions, processing them by ensemble evaluation, which was not possible with WEB-HIPRE. In the panel meetings, normal distributions were used for health, costs, and waste. Time limitations did not allow for the exploration of uncertainties in the subjective criteria such as feasibility and willingness to cooperate. Uncertainties obtained by the calculations performed in the ERMIN2 model were included as parameters for the normal distribution of the amount of waste. Because a representation of the results of an ensemble evaluation in stacked bars does not provide information on the uncertainty included, the MCDA tool has several options to visualize the uncertainties in additional graphs (Müller et al. 2020). The discussion facilitator has the liberty to choose between various graphical outcomes such as bars, box and whiskers, ranking bars, or ranking bubbles. Figure 6B shows the outcome of the MCDA ensemble evaluation in ranking bubbles that represent how many times a recovery strategy ranked first, second, et cetera, where the size of a bubble reflects the proportion of how many times a strategy ranked at that specific place place. A single bubble for a strategy would indicate no uncertainty at all, whereas more and more equally sized bubbles would indicate high uncertainty. The figure shows that there is more uncertainty in the ranking of the 2 low waste strategies with relocation than, for example, in the high waste strategy with relocation, which apparently ranked last place most of the time. The Slovakian panel members indicated that they appreciated the visualization of these uncertainties.

Limitations to the study

Although the various panel meetings were prepared with the utmost care, limitations in the present study were inevitable. First of all, not all stakeholders invited were able to participate in the panel meetings. Nevertheless, the panel meetings managed to be a good representation of stakeholders normally involved in decision-making after a nuclear accident. Stakeholders present included both national and local governmental decision makers as well as experts representing the views of citizens involved in a nuclear accident. As such, the panel meetings approached a real-life situation in the transition phase of a nuclear accident. Nevertheless, in a real-life situation preferably societal organizations are involved in the decision-making process. Therefore, it would be worthwhile to start involving such organizations in the resiliency planning of a nuclear accident and motivate them to participate in preparatory exercises. A different panel composition may come up with a different set of criteria to include. Nevertheless, the outcome of the present study shows that although the case studies and the stakeholders

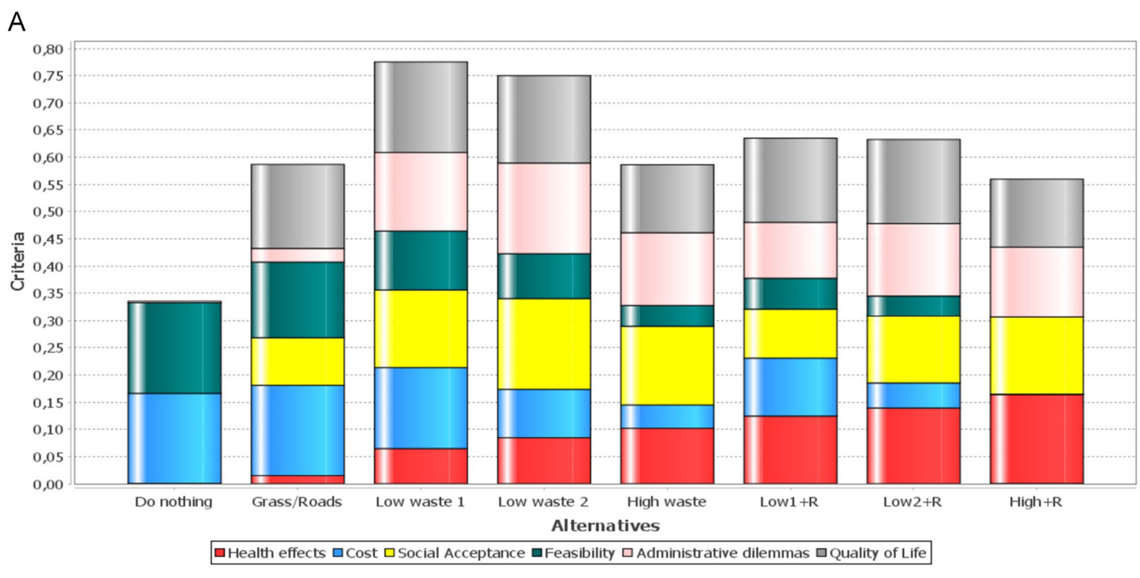

Figure 5. Outcome of the MCDA in the Dutch panel using equal weighting for the various criteria (A) or the following weights for the criteria Health (w = 30%), Costs (w = 10%), Social acceptance (w = 30%), Feasibility (w = 10%), Administrative dilemmas (w = 10%), and Quality of life (w = 10%) (B). The variance around the stacks decreases in the following order from high waste + R, low waste 2 + R, high waste, low waste 1 + R, low waste, grass/roads, do nothing. MCDA = multicriteria decision analysis; R = relocation.

B

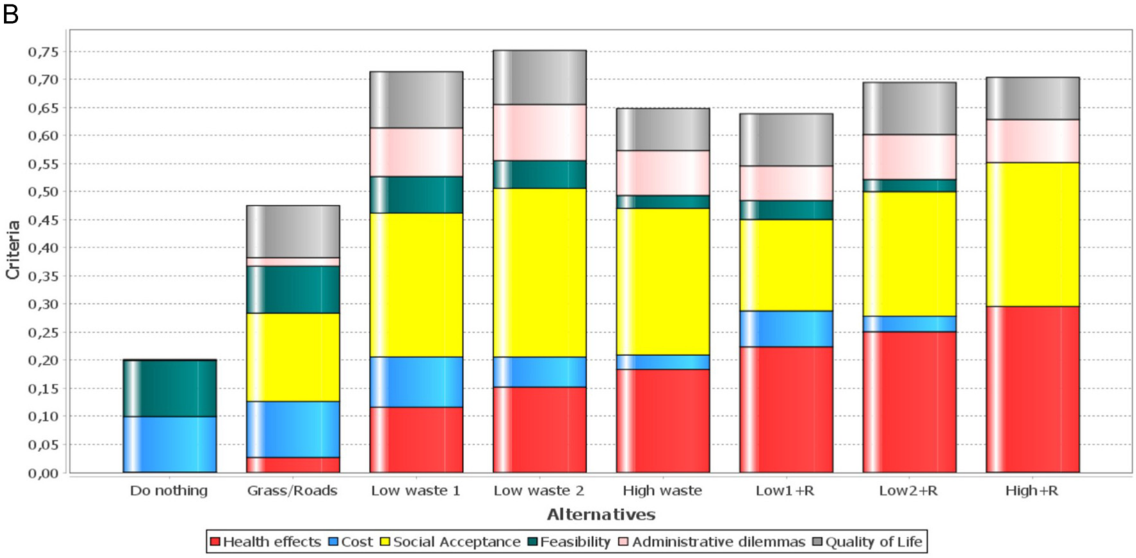

Figure 5. Continued.

involved differed between the Dutch and Slovakian panel meetings, common criteria could be identified that were seen as relevant to include in the MCDA tool, that is, health effects, costs, feasibility, and social acceptance. These 4 key criteria are likely to be included in any stakeholder panel that discusses a nuclear accident (see, e.g., Geldermann et al. 2009); although sometimes framed differently, for example, costs may be part of feasibility (Mustonen 2005; Geldermann et al. 2009).

A different set of stakeholders may, however, impact the quantification of the subjective criteria (such as feasibility or social acceptance). Therefore, it is recommended to further explore these subjective criteria to determine how such attributes can be valued and/or how they can be included in

A

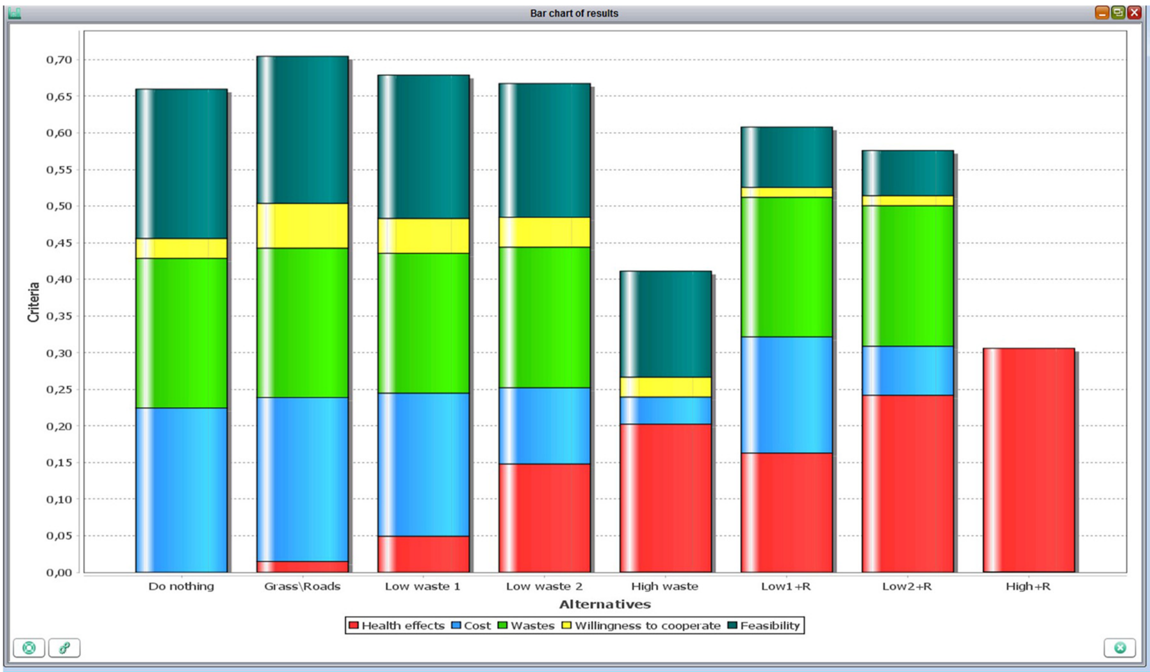

Figure 6. Outcome of the MCDA in the Slovakian panel presented (A) in bar charts (the heights of the criteria in each bar represent the contribution of the criterion to the optimal solution) and (B) in a bubble graph. Each bubble reflects how many times a specific strategy (column) scored a specific rank (row) during an ensemble evaluation, where the size corresponds to the number of times the rank was achieved. A single (large) bubble for a strategy, thus, indicates no uncertainty, while an increasing number of (smaller) bubbles indicates an increasing uncertainty. The strategies are sorted from left (worst) to right (best) based on a performance value that is derived from the ranks they scored. Thus the most preferable strategy is the farthest right one indicated by the largest bubbles in the top right corner. MCDA = multicriteria decision analysis.

B

Figure 6. Continued.

the decision-making process. When strict expert elicitation is used, the AHP may be applied, which is based on a pairwise comparison of alternative strategies (Saaty 2008). The developed MCDA tool allows for the inclusion of an AHP for the various criteria.

The criteria health and costs are seen as objective and could be estimated prior to the panel meetings. Nevertheless, these estimations also are not fully objective and incorporate uncertainties. The MCDA tool allows the inclusion of these uncertainties by using probabilistic rather than deterministic values. The health effects currently incorporated in the tool estimated the direct impact on human health in the number of fatal cancers to be expected from a nuclear accident. However, psychosocial effects are also relevant to include. Evaluation of the Fukushima accident showed that residents of the area show traumatic symptoms, especially the evacuees (Yabe et al. 2014). However, in order to incorporate this aspect in the health criterion, a separate study is needed to include these psychosocial effects in the attribute table. Sociological studies are needed to explore the effect of different recovery strategies on the residents' quality of life. Lessons can be learned from previous accidents. For example, Hirosaki et al. (2018) investigated the effect of changes in lifestyle after the Fukushima accident on the happiness of people using the frequency of laughter as an indicator. Alternatively, risk indicators such as disability-adjusted life years (DALYs), quality-adjusted life years (QALYs), or loss of life expectancy (LLE) might be measures that enable the comparison of indirect health effects of various recovery strategies (Murakami 2018). Further research is needed in order to incorporate these psychosocial effects in the decision-making process.

CONCLUSIONS

In the present study, the usefulness of an improved MCDA tool was tested in panel meetings where the consequences and potential countermeasures in the transition phase of a fictitious nuclear accident were discussed. According to the panel members, the use of MCDA allowed for the identification of strategies that are clearly not viable due to a low score on the relevant criteria. Furthermore, the MCDA tool allowed for a transparent decision-making process that enabled a structured discussion among relevant stakeholders on the possible recovery strategies and their pros and cons in the transition phase of a nuclear accident. As such, the use of an MCDA tool can be part of national response plans because these plans currently primarily focus on the emergency phase. The tool allows different weights for the criteria to be incorporated, which helps to select and justify a set of the best scoring alternatives that can be presented to the final governmental decision makers for further evaluation. The tool can also be deployed during exercises for nuclear emergency preparedness that support the process of the radiological protection culture development and stakeholder engagement. Because the tool allows for comparing various recovery strategies using a range of evaluation criteria, it is not limited to use after nuclear accidents but also could be applied in resiliency planning for any accident that requires an extensive cleanup and/or (medical) monitoring such as a dirty bomb attack or chemical releases.

The present study showed that the MCDA tool facilitated communication with the stakeholders because the adapted tool includes a narrative report and allows for graphical representations of the outcome and uncertainties in this outcome. These features were appreciated by the panel members and were seen as added value compared to the previous WEB-HIPRE tool. Presenting the uncertainties shows that even though 1 recovery strategy may come out as the best option, there is uncertainty around this decision. As such, it is clear that the results should not be seen as "the truth," but rather they serve as an aid to streamline discussions among stakeholders. The output can, thus, be used to support the decision makers, but it will not replace their final decision.

Acknowledgment—Stakeholders who participated in the panel meetings are kindly thanked for their active involvement in the discussions around the fictitious nuclear accident. The partners within WP4 of EU project CONFIDENCE are acknowledged for their cooperation in the general preparation of the panel meetings. EU project CONFIDENCE is part of the CONCERT project. This project has received funding from the Euratom research and training programme 2014–2018 under grant agreement No 662287. Milagros Montero Prieto and Cristina Trueba Alonso (CIEMAT) are kindly thanked for providing the scenario for the fictitious nuclear accidents. The help from Tom Charnock (Public Health England) with the ERMIN calculations is greatly appreciated. Wolfgang Raskob (Karlsruhe Institute of Technology) is acknowledged for his help in preparing the second panel meeting. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement—Upon request, people interested can obtain the MCDA files that include all data used to decide on the optimal recovery strategy.

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 DOI: 10.1002/ieam.4375