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PAPER

Demonstrating the use of a framework for risk-informed decisions with stakeholder engagement through case studies for NORM and nuclear legacy sites

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Abstract

The international community has come a long way in developing a consensus that the remediation and management of naturally occurring radioactive materials and nuclear legacy sites will benefit from the use of the framework for risk-informed decision-making. Such a framework should ideally integrate risk assessment and decision-making. The framework presented in this paper specifically addresses the needs and expectations in the wider socio-economic and environmental context, as well as a narrower human health context. The framework was demonstrated as part of the International Atomic Energy Agency's second Modelling and Data for Radiological Impact Assessments Programme. Three case studies, which have used or could use this integrative approach, are used for illustration. The first concerns remediation from uranium mining activities at Beaverlodge Lake in northern Saskatchewan, Canada, engaging stakeholders (also called 'interested parties') in the decision-making process on further options. The second case study suggests how decision analysis could support the selection of the best option for waste disposal for uranium ore processing at Žirovski vrh, Slovenia, taking into account a potential landslide and migration of waste throughout the adjacent valley in the event of flooding. The third case study presents the process and results of radiological safety assessment of the Kepkensberg sludge basin in Tessenderlo area, Belgium both before and after the disposal of material from remediation of the nearby Winterbeek River. It illustrates how such assessments could interface with decision analysis for the purpose of supporting the regulatory decisions related to future approval of a waste disposal option. Results show that formal stakeholder engagement in decision analysis provides a strong contribution to objective, robust, and transparent decision-making not only for radiation protection area but also in others where health and environmental impacts are of concern. A number of recommendations for future work have also been made.

1. Introduction

Assessment of radiation doses and corresponding risks to humans and the environment requires the consideration of many features, events, and processes (van Dorp 1994, OECD 2000). For a particular environmental system, a variety of radionuclide transport and transfer processes take place leading to specific exposure conditions. Moreover, in accordance with the radiation protection principle of optimization of protection and safety, the risk assessment (RA) and management need to take into account a much wider range of socio-economic, land use, environmental policy and other issues in addition to those related to human health (IAEA 2014, 2022, Yankovich *et al* 2022 in this special issue). There is also a general need in many societies to engage stakeholders in the decision-making and remediation process and consult with them throughout the process. To address this overall need for risk-informed decisions with stakeholder engagement, with specific focus on the remediation of naturally occurring radioactive materials (NORMs) and nuclear legacy sites, the International Atomic Energy Agency (IAEA) established working group 1 on assessment and decision-making of existing exposure situations for NORM and nuclear legacy sites as part of the second Modelling and Data for Radiological Impact Assessments (MODARIA II) Programme. This integrated the related efforts in two working groups under MODARIA I regarding remediation strategies and decision aiding techniques and NORM and nuclear legacy sites (note: in terms of the term 'nuclear legacy' we understand that it pertains to residues—material and non-material—for which due care need to be taken as to avoid/minimise future detrimental consequences. This is in accordance with the NEA's description of the term and the caveats regarding its strict definition (NEA 2019)).

In both the MODARIA I and MODARIA II Programmes, decision-making on remediation was specifically discussed. MODARIA I focused on decision-aiding tools and processes for planning and implementation of remediation, with some emphasis on potential means to engage with stakeholders. That work also provided a high-level overview of decision analysis and surveyed many evaluation tools from several schools of decision analysis. The MODARIA II Working Group 1 had a subtly different objective of providing demonstration and guidance to support the decision-making through case studies involving remediation of sites (IAEA 2016). In particular, it emphasized an ongoing and iterative deliberation process between regulators, stakeholders, and experts. Several comparison studies were, therefore, undertaken to provide information on the applicability of the different RA tools considered, their different strengths, the consistency that might be expected between their results, and their appropriateness for different management decisions and contexts. These efforts are among the various other efforts of the IAEA and other international programmes that have common interests in this area, such as: the update of IAEA WS-G-3.1, which will be superseded by IAEA General Safety Guide, GSG-15, on remediation strategy and process for areas affected by past activities or events (IAEA 2022, Yankovich *et al* 2022 in this special issue); network on environmental management and remediation—determination of environmental remediation end states (ENVIRONET—DERES), intended to produce guidance on the determination of site end-state in remediation of different sites (IAEA 2020); risk perception, communication and ethics of exposures to ionising radiation (RICOMET); NEA EGLM—Nuclear Energy Agency Expert Group on Legacy Management (NEA EGLM) (NEA 2019); EU projects aimed 'to enhance uncertainties reduction and stakeholders involvement towards integrated and graded risk management of humans and wildlife In long-lasting radiological exposure situations' (TERRITORIES); and coping with uncertainties for improved modelling and decision making in nuclear emergencies (CONFIDENCE), established to perform radiation protection research focused on uncertainties in the area of emergency management and long-term rehabilitation. Among similarities of all these efforts we emphasize similarities of EGLM conclusions and recommendations with MODARIA work. One of these is uncertainty due to lack of data and records about nuclear legacy sites and their remediation which makes life difficult to regulators and also to managers and other stakeholders in terms of optimising decisions. A way out in such situations is wide stakeholder engagement and consultation with alocation of responsibilities, a holistic approach with sharing experience in planning and considering different types and aspects of hazards/impacts (e.g. competing safety interests, as between radionuclides, other contaminants and other hazards, and that this should be done on a balanced and proportionate basis in terms of assessment methods and criteria), options for their solution, different exposure situations, and prescriptive and performance-related regulations. The latter need to apply follow-up evaluations of the effectiveness and success of implemented protection option together with the concerned parties (stakeholders). All these issues have been considered in MODARIA II WG1 work and are captured in figure 1(b) with related recommendations.

Our aim in this paper is to present a framework for risk-informed decision analysis with engagement of stakeholders in deliberations on remediation and post-remediation management, recognising the wider context of the problem. We advocate the participation of stakeholders in a formalized, structured, decision analysis process and demonstrate this approach through three case studies for existing exposure situations needing remediation in which the proposed framework has either been used or could have been used. The first case study concerns remediation from uranium mining activities at Beaverlodge Lake in northern Saskatchewan, Canada. The study sought further remediation options by engaging stakeholders to obtain informed, clear, and documented feedback about the predicted benefits and costs of a range of remediation

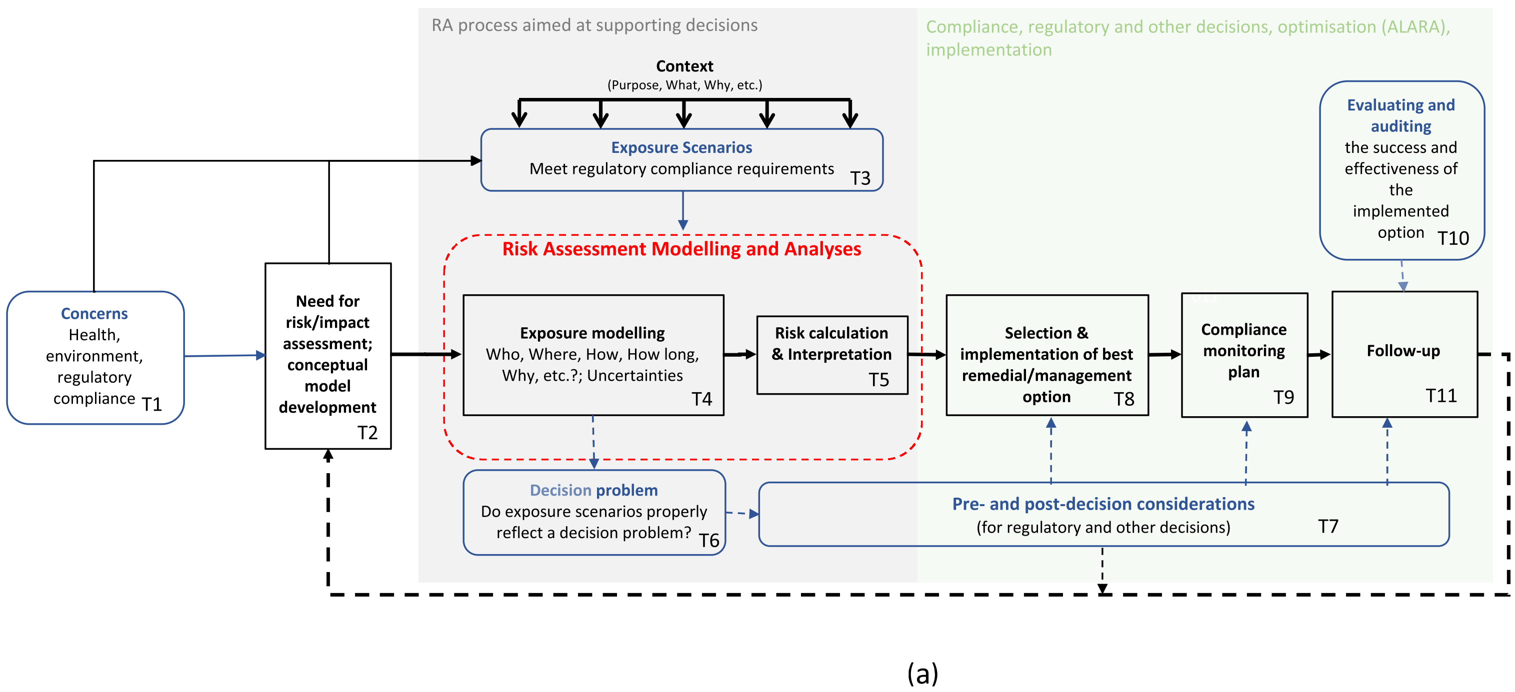

Figure 1. (a) The traditional approach to modelling in remediation and regulation. (b) The use of decision analysis within remediation and regulation to articulate discussions between all stakeholders.

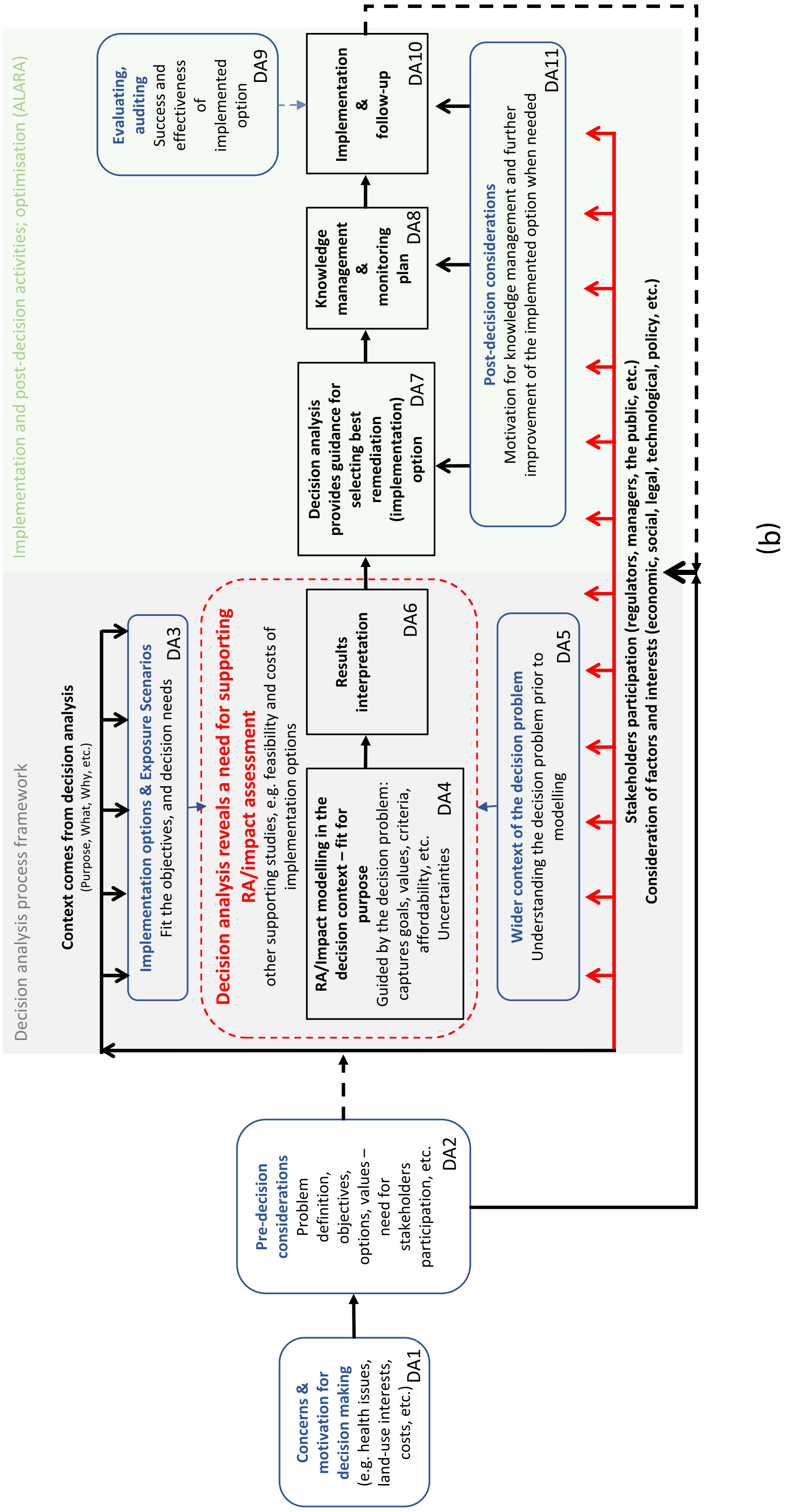

Figure 1. (Continued.)

options. The second case study illustrates how decision analysis could support the selection of the best option for waste disposal for uranium ore processing material at Žirovski vrh, Slovenia (RŽV), taking into account the potential for a landslide and migration of waste throughout the adjacent valley in the event of flooding (Križman and Zabric Bilić 2016). The third case study presents the process and results of radiological safety assessment of the Kepkensberg sludge basin in Belgium both before and after the disposal of material from remediation of the nearby Winterbeek River (see Pepin *et al* 2022 in this special issue). This study suggests how such assessments could interface with decision analysis for the purpose of supporting the regulatory decision-making process related to future approval of a waste disposal option.

Remediation and post-remediation management of radioactive contamination[10] normally involve four main activities (see also IAEA GSG-15; IAEA 2022):

(a) initial gathering of available site-specific information, including the possibility of implementing a site characterization study and identifying the potential need for remediation (i.e. to determine whether or not remediation is justified), identifying stakeholders and their interests, and selecting appropriate remediation criteria, including those related to regulatory compliance;
(b) identification of remediation options and their optimization in the broadest of senses balancing all objectives, followed by subsequent development and approval of the remediation plan;
(c) implementation of the remediation plan; and
(d) post-remediation management with possible release from regulatory control of all or part of a site from regulatory control.

Following the completion of each of these main activities, a decision should be made about whether to release the site (or part of it) for either restricted or unrestricted use or to proceed to the next activity (IAEA 2020). To support these decisions, assessment of radionuclide environmental transport and transfer and the potential risks to human health and the environment is needed to demonstrate compliance with regulatory requirements and the rationale for the safe use of remediated areas in the future. In recent years, decision-making regarding radioactivity on NORM and nuclear legacy sites has been moving towards using a risk-informed, performance-based approach (e.g. National Research Council 2014, IAEA 2019, 2022). The term, 'risk-informed decision-making', pertains to the assessment of human health and the ecological risk to support a decision-making process, as appropriate. However, there are many other contributing factors or objectives that inform a more complete decision analysis, such as worker safety, economic (cost) constraints, financing and insurance, economic health and employment of local communities, stakeholder expectations and preferences, environmental justice, and others (IAEA 2002, 2022, NUREG 1757 2006). Considerations such as these are increasingly being considered when addressing decommissioning, remediation, and waste management issues in a holistic manner that accommodates other relevant objectives in addition to regulatory compliance (IAEA 2002). The intent is to find the most appropriate solution that meets the objectives of the decision makers and stakeholders. This risk-informed decision-making process places traditional human health and ecological RAs within a more complete decision analysis structure. In this way, RA and decision analysis are interconnected activities; while RA provides the toolsets and risk information that are a valuable input to decision-making, decision analysis can identify the specific needs and guide the selection of exposure scenarios for conducting the RA, or can be used as part of justification and optimization in selecting feasible remediation options (IAEA 2020). This comprehensive approach to decision-making also articulates the deliberations that are necessary between regulators and other decision makers, while also drawing in and engaging additional stakeholders in the discussions (IAEA 2002).

Figures 1(a) and (b) illustrate the broad differences between the traditional approach to the use of RA modelling in the process of remediation within the legal and regulatory framework and the more participative, deliberative approaches that use decision analysis to organize the whole process, specify all the objectives, uncertainties, and concerns driving the process, and, in particular, involve stakeholders throughout, articulating discussion and building a shared understanding of the issues. The latter is emphasized by red arrows at the bottom of figure 1(b). The transparency, explicit reasoning, and auditability brought through formal decision analysis feeds naturally into the planning, knowledge, and process management needed during the implementation stages, which can take several years. The structured, explicit, auditable reasoning brought by decision analysis is also promoted in other literature, such as policy analysis, life cycle costing, and risk management (Miettinen and Hämäläinen 1997, Aven 2003, Daniell *et al* 2016).

[10] That is, those that are affected by contaminated residues from, for example, the mining industry (uranium, metals, etc), the phosphate industry, or past nuclear research or production activities. We note that the modelling tools and processes that are recommended herein have a much wider applicability to managing the risks from radioactivity arising, for example, from decommissioning and radioactive waste management.

In comparison with the traditional approach in figure 1(a), the participative, deliberative decision analysis with stakeholder engagement in figure 1(b) offers the advantages of addressing the following questions:

- does the scale of health, environmental, economic, and other risks justify a full analysis of possible remedial measures?
  Activities DA1 and DA2 in the pre-decision phase in figure 1(b) include more detailed consideration of the wider concerns and motivations for decision-making, problem definition, clarification of objectives than those activities in T1 and T2 of figure 1(a).
- How can an optimum decision be made for managing a particular contaminated area, considering all relevant contributing factors, for example, environmental and ecological impacts, worker safety, land use, environmental justice, and remediation costs?
  Activities DA1 and DA2 in figure 1(b) are more comprehensive than those in T1 and T2 in figure 1(a), ensuring that interests of stakeholders are appropriately identified and represented. Activities DA5 and DA11, then, encourage active and effective participation of these stakeholders in the evaluation and deliberation stages.
- What are the preferred, optimal remediation options?
  The decision analysis modelling and other supporting studies in activities DA4 and DA6 in figure 1(b) consider a broader range of objectives and contextual issues from DA3 than the radiation risk modelling of T4 and T5 in figure 1(a), driven by the focus on regulatory requirements in T3. It should be noted that there may be iterations between DA3, DA4, and DA6 as the analysis identifies further issues.
- Can it be demonstrated that the preferred remediation options can be undertaken safely, i.e. such that the implementation risks address competing safety interests, for example worker health and environmental protection, as between radionuclides, other contaminants and other hazards, and that this should be done on a balanced and proportionate basis in terms of assessment methods and criteria, and that are kept as low as reasonably achievable (ALARA)?
  This is a long-lasting task consisting of targeted risk and impact assessment, followed by knowledge management and further improvement of the implemented option when needed, regular auditing of the success and effectiveness of implemented option, and looping the results back to stakeholder participation in support of confidence building (activities DA7, DA8, DA9, DA10, and DA11 in figure 1(b)). Activities T7, T8, T9, T10, and T11 in figure 1(a) have a much narrower focus on regulatory issues.
- In addition to regulatory requirements, can long term safety be demonstrated in a manner that achieves public confidence?
  The continuous stakeholder participation with transparent iteration and feedback of key information throughout the decision-making process and implementation are designed specifically to foster and ensure public confidence (activity DA11 in figure 1(b)). Stakeholders are not explicitly involved in the activities in figure 1(a), though they may be informally involved.

In summary, operational differences between traditional and participative, deliberative approach could be described as follows:

- if one needs (wants) to demonstrate meeting requirements based on IAEA Basic Safety Standards or other quantitative standards and regulatory conditions which are scientifically adducible the usage of the process as described in figure 1(a) is adequate, while
- if such demonstration is to include stakeholder support then usage of the process as described in figure 1(b) is needed. Such approach is supported and further argumented by OECD NEA Forum on Stakeholder Confidence, naming it 'added value' in the very recent document explaining key terms on stakeholder confidence related to radioactive waste management (IAEA 2003, Lindborg *et al* 2022, NEA 2022 in this special issue).

Although the working group focused its attention on the objectives of remediation of NORM and nuclear legacy sites, we note again that the methodologies that we discuss here are also applicable to decision-making related to decommissioning, nuclear waste management, and, indeed, all decision-making related to managing the risks arising from radioactivity or other types of hazards. This is demonstrated in the IAEA's document on integrated approach to planning the remediation (IAEA 2009) which highlights the importance of linking decommissioning to remediation. Among other similarities between messages in this document and MODARIA II WG1 work, such as the role of non-technical (including value based) factors in decision making, it is important to note common ideas behind figures 1 and 2 in the IAEA document and figures 1(a) and (b) in this paper, especially the assessment and decision contexts as they are emphasized there.

2. Risk assessment, decision analysis, and the process of decision-making

Before presenting the details of case studies in relation to figures 1(a) and (b), it will be helpful to first discuss, more generally, the concept of decision analysis and its relationship to RA. The approach adopted here is generally known as Bayesian (French and Rios Insua 2000, French *et al* 2009, Goodwin and Wright 2009, Gregory *et al* 2013, Keeney 2013, Abbas and Howard 2015), which includes the following features:

(a) it provides a comprehensive approach to dealing with uncertainty and value judgements in very sophisticated models;
(b) it is based on a well-established and explicit set of principles of rationality;
(c) it can draw evidence from both hard data and expert judgement;
(d) simpler, compatible sub-models can be used to focus on specific issues; and
(e) there is considerable experience in its wide application.

Figure 2 provides a broad overview of the Bayesian approach, which typically separates the issues into two distinct perspectives:

- Science: What might happen? This is where the scientific knowledge of the situation enters the analysis. What remedial actions might be taken? What will be the consequences of these actions? How uncertain are the consequences?
- Values: How much do the different potential consequences matter? This is where the decision makers and stakeholders have to deliberate on the impact that the consequences will have on each party.

The science side of the figure corresponds broadly to conventional RA, including modelling of uncertainties with probabilities. If, as is often the case, there is a need to acquire more data to reduce the uncertainties, prior assessments are combined with the data to update the probabilities (Zapounidis and Pardalos 2010, Parnell *et al* 2013). Also tiered or graded approaches to assessments, e.g. ERICA, are useful in such situations where later stages of assessments may apply information from most recent studies (Beresford *et al* 2007, IAEA 2009; Brown *et al* 2016).

The values side corresponds to what may have been conducted, in the past, by deterministic cost-benefit analysis. The Bayesian approach extends this by using multi-attribute utility functions, which enable easier valuations of non-tangibles (e.g. preferences for different possible outcomes of a decision), a formal introduction of attitudes to risk in the face of uncertainties, and more intuitive support for deliberations between decision makers, regulators, and other stakeholders (Sjöberg 1999, Slovic 2000, Andersson 2001, IAEA 2002, 2009, Dyer 2005, Hsu and Sandford 2007, Ishizaka and Nemery 2013, French and Argyris 2018). The methods described in these references have been used in many environmental areas including nuclear safety and radiation protection. But the uptake is not as full as we would wish (Modaria I and II working groups 1 would not have happened if they were!). French and Argyris (2018) discuss some of the problems in making them more commonly used. Given the length of the current paper we feel that to explore case studies and the reasons that we are still promoting them after a couple of decades from their first use would be to extend the paper beyond our main aims. The science and values perspectives are drawn together by exploring expected utility rankings through a variety of sensitivity and robustness analyses. If discussions suggest that important elements may have been omitted from the modelling and analysis, the process may iterate until the decision makers feel that they have gained enough understanding that the analysis is adequate, i.e. it is sufficiently detailed for them to make a confident decision. On the right, the figure shows the three decision-making steps:

- Pre-decision—general discussions and investigations in which the issues are formulated and modelled.
- Decision-making—a range of quantitative explorations of the model(s) to build an understanding of the issues, their balance, and ultimately, to recommend a decision.
- Post-decision—interpreting the model recommendation into real-world actions and risk managing their implementation.

2.1. Brief description of the case studies

2.1.1. Case study 1: Beaverlodge

During the period of 1952–1982, uranium mining activities, on a site with three mineshafts and significant underground workings, took place north-east of Beaverlodge Lake in northern Saskatchewan, Canada. There

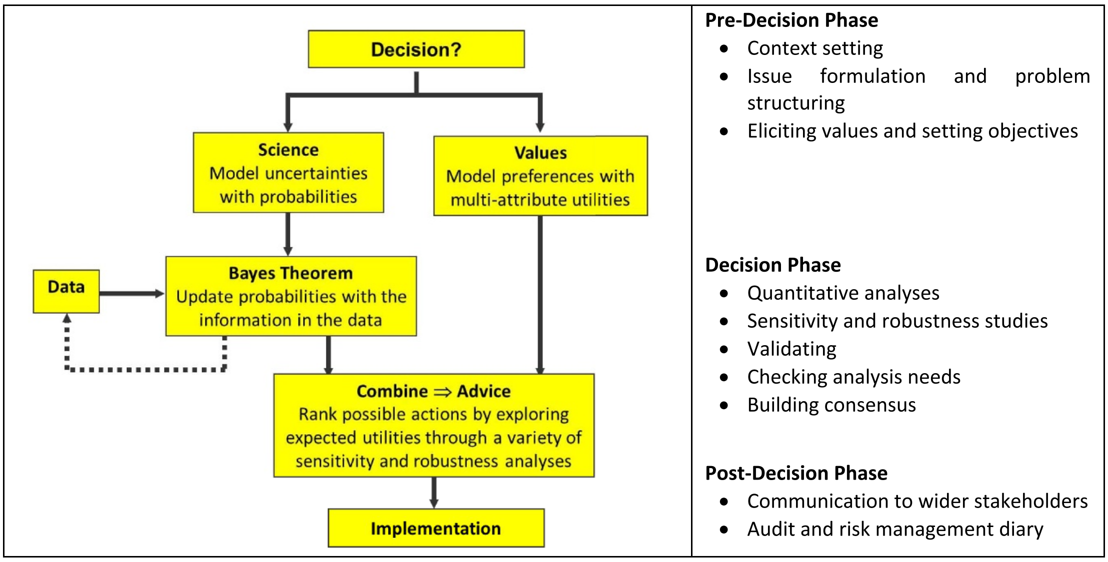

Figure 2. Bayesian RA and decision analysis.

are many lakes and other aquatic features in the area. From 1982 to 1985, the Beaverlodge mine was decommissioned and reclaimed following a plan approved by the federal and provincial regulators. This was the first Canadian uranium mining operation to be subjected to regulatory approval of a formal decommissioning and remediation strategy. Since 1988, the Cameco Corporation, henceforth Cameco, has conducted environmental monitoring and investigations, as well as necessary maintenance on the decommissioned Beaverlodge properties, on behalf of the Canadian Government (Cameco Corporation 2012, Webster and Hockley 2013). This monitoring and maintenance phase had been expected to last some 10 years from the end of decommissioning in 1985, but had to be extended, as there was no acceptable regulatory framework to accept the decommissioned properties back to Provincial Government (Province of Saskatchewan) control. In addition, during the post-remediation period, there were increased regulatory expectations and requirements; for example, for both uranium and selenium in aquatic environments. In 2007, the Saskatchewan Institutional Control Program was introduced with legislation establishing further regulatory requirements for decommissioned sites. The programme also established a process through which sites, once acceptably remediated and released from regulatory control, could be returned to the Province. This catalysed a process of investigating potential remediation options that could be reasonably implemented on the Beaverlodge properties to address residual risks, and in 2009, a process of engagement with stakeholders was initiated, recognising a wide range of criteria.

The decision-making process had the overall objective of obtaining informed, clear, and documented feedback about the predicted benefits and estimated costs of a range of remediation options from a range of stakeholders. It involved three broad stages. Firstly, an options identification workshop was held in 2009 with key interested parties to build a common understanding of all issues and concerns, possible remediation techniques, and investigations that would need to be completed before any detailed remediation strategy could be specified and initiated. The second stage involved many investigations and quantitative analyses to predict the effectiveness of different remediation options. The third stage again brought together the interested parties in an options evaluation workshop to undertake a more detailed evaluation of possible remediation strategies and provide feedback for Cameco to consider while developing the path forward. After the 2009 workshop, Cameco identified over 20 studies that needed to be performed, which they undertook in the three years that followed. These were used to facilitate the development of a quantitative site model (QSM), which modelled the environmental transport and pathways. The QSM enabled the prediction of concentrations of constituents of potential concern (e.g. uranium, radium, and selenium) and predicted changes in the residual risk profile as a result of the implementation of various remedial actions being considered. In addition, Cameco estimated the order of magnitude costs for each of these potential remediation options.

In April 2012, a further workshop was held to discuss and evaluate remediation strategies. Cameco used the results of the options evaluation workshop in developing a path forward plan (Cameco Corporation 2012).

2.1.2. Case study 2: Uranium mine at Žirovski vrh (RŽV), Slovenia

The uranium mine at Žirovski vrh consists of three main facilities (the Mill Site, the Waste Pile Jazbec, and the Mill Tailings Boršt). The mine is in the last phase of closing. Two facilities have already been remediated and closed: the Mill Site was remediated and turned into an economic zone in 2000 and the Waste Pile Jazbec was closed in 2012. The third facility—the Mill Tailings Boršt—is still under remediation. The site is on a hill above the inversion altitude to allow for radon dispersion and to minimize its impact on the population in the adjacent valley. Altogether, around 610 000 tons of the tailings are deposited in this facility, total activity is 48.8 TBq (Resolution 2016). The waste at Boršt started sliding down after a heavy rainfall event in November 1990. The sliding velocity was in the range of several cm/year. To control or stop the sliding, a drainage tunnel was constructed in 1995, but it was not effective. After subsequent heavy rainfall events—the last in 2016—the regulatory authority the Slovenian nuclear safety administration (SNSA) required improvement of the drainage efficiency with consideration of additional monitoring. There was concern about waste slipping down to the adjacent valley and widely dispersion throughout the valley in case of flooding. A preliminary dose assessment for individuals living in the valley showed values exceeding the annual dose limit of 1 mSv yr^{-1} (Križman and Zabric Bilić 2016). The final closing activities have been deferred until the remediation provides dropp of the sliding velocity to the required 1.5 cm yr^{-1} (Safety report on remediation of Mill Tailings Boršt 2007, Geotechnical report 2010, Resolution 2016). This requirement has still not been achieved (Klemenčič 2019), next evaluation is planned in 2021 (Klemenčič 2020).

The overall situation and approach to identifying and comparing remediation options have been regularly discussed since 1990. In 1994 and 1995 the first comparative evaluation of the three possible remediation options (options A, B, C—see brief description below) has been made (IJS 1995). Option A with a drainage tunnel as the key measure against sliding of the waste was selected in 1995. The tunnel did not stop sliding, only reduced its velocity to 2–7 cm yr^{-1} (Klemenčič 2019). The most recent discussions in 2018 with the regulators—the SNSA, the Ministry of the Environment and Spatial Planning (MESP), the Mining Inspectorate at the Ministry of Infrastructure (MI), and the Agency for Radioactive Waste Management (ARWM) led to the identification of two possible approaches to final remediation: SNSA and the ARWM proposed further work to improve the performance of the drainage tunnel, while MESP suggested developing a more comprehensive RA as a basis for final decision-making, although MESP did not articulate how the results of this assessment will be used in decision-making (Kontić 2018, MODARIA II WG1 Interim Meeting 2018). MI has not expressed an opinion on the issue yet. Moreover, the participation of stakeholders in the decision process was not defined; therefore, further discussion and agreement are needed. One of the basis for this discussion is the decision analysis and its results as presented in this paper.

The remediation options identified and discussed since the early 1990s include the following:

- Option A: maintaining the status quo, involving additional work to improve the efficiency of the drainage tunnel with the aim of preventing further sliding of the waste;
- Option B: removing the tailings and disposing of them in the mine pits for long-term (permanent) isolation of the waste;
- Option C: removing the tailings and disposing of them at the Jazbec site to avoid the sliding and incidental dispersion of the waste throughout the adjacent valley in case of heavy rains.

After selecting option A in 1995 the other two were not actual any longer.

2.1.3. Case study 3: Tessenderlo area, Belgium

This case study deals with remediation of the area contaminated by past activities by the company, Tessenderlo Chemie (TCH), which processed phosphate ore for the production of dicalciumphosphate. Details of the situation and the need for remediation can be found in the article by Pepin *et al* (2022) in this Special Issue of Journal of Radiological Protection.

The decision context for the remediation concept of the Tessenderlo area is complex; radiation protection considerations are not the driving factor in the decision-making process. The significant chloride and contamination by heavy metals also form the basis of the risk analysis and the remediation plan for the Winterbeek River. Remediation needs to comply with the overarching goals of achieving ecological restoration of the marshland area adjacent to the site, and of integrated water management—including the control of flooding in the area.

2.2. Decision analysis methods and tools

The decision-making process for the Beaverlodge site followed the method described in the literature (French *et al* 2009, Goodwin and Wright 2009, Gregory *et al* 2013, Parnell *et al* 2013), similar to that depicted in figure 1(b). It is the Bayesian decision analysis method that combines scientific data with preferences (i.e. values someone places on something, e.g. objectives, concerns) towards ranking the possible actions according to expected utilities.

For the RŽV case study, two decision analysis tools were used: decision expert—DEXi (Bohanec 2020); and Guided Interactive Statistical Decision Tools—GiSdT (Neptune and Company Inc 2017). DEXi applies DEX methodology; it is a hierarchical and qualitative multi-criteria decision-making method (Dyer 2005, Saaty 2008, Bohanec *et al* 2013, Moshkovich and Mechitov 2013, Trdin and Bohanec 2014). GiSdT applies structured decision-making (SDM) evaluation.

For the RA of the Kepkensberg/Tessenderlo case study, the IAEA's Improvement of Safety Assessment Methodologies (ISAM) approach (IAEA 2004) was followed. Several RA tools were applied, including, for example, Amber, the NORMALYSA (NORM and Legacy Site Assessment) software tool, and RESRAD-OFFSITE (Pepin *et al* 2022 in this special issue).

3. Results

3.1. Results of applied decision analysis and RA

3.1.1. Case study 1: Beaverlodge

As mentioned earlier, there were three phases of the decision analysis process for Beaverlodge site remediation: The Options Identification Workshop; the investigations; and the options evaluation workshop (Webster and Hockley 2013). Due to space limitations of this paper, we have only summarized the results of the third phase. The options evaluation workshop began with a presentation of remediation options to the participants. Each option was fully described, including its remedial effects as predicted by the QSM and its estimated cost. The modelling assumptions that had been made were also clearly explained. Once each option had been presented, participants were asked to identify the most pertinent 'pros and cons'. This stimulated a discussion of the option itself, as well as an exploration of the assumptions underpinning the QSM modelling and cost estimates. Each group of interested parties then evaluated each option. The evaluations were captured in a consistent manner using agreed terminology with each group stating whether it 'strongly agreed', 'agreed', 'disagreed', or 'strongly disagreed' with each statement (see table 1 for an example). When there was significant disagreement between the various interested parties, the reasons for the disagreement were discussed and captured. However, despite the varied perspectives of the participants, there were many points of agreement and consistent evaluation of options. The 'do-nothing' option was found to be unacceptable by all participants. In general, however, participants did not think that large-scale remediation options would improve environmental conditions or reduce ecological or human health risks, at least not in relation to their high cost. There were a few options identified that had relatively low cost and measurable local benefit, and all groups agreed that those should be the focus of further actions. Cameco used the results of the options evaluation workshop in developing a path forward plan for remediation of the Beaverlodge properties (Cameco Corporation 2012).

3.1.2. Case study 2: RŽV

In DEXi, option suitability is the top attribute of the decision problem. Attribute scales determine the qualitatively expressed categories that each attribute can attain (e.g. high, medium, low; not suitable, less suitable, suitable, excellent; and each of these have appropriate and transparent quantification behind them). Utility functions determine how different combinations of lower attribute values aggregate into the values of the attributes above them. Based on the utility functions, the decision model aggregates each of the option values from the bottom up (Bohanec *et al* 2013).

The result of the decision analysis, as presented below, has been produced without participation of regulators or stakeholders. Besides a review of the decision analysis and decision-making up to 2019, especially with regard to the consideration of remediation options A, B, and C in 1990s, its aim was to investigate what additional remediation work could be appropriate in the current situation to prevent the sliding at Boršt.

The evaluation using GiSdT was based on the objectives to be achieved by each of the remediation options. The hierarchy of objectives was determined based on assumed preferences of stakeholders (figure 3). Categorical or continuous measures were determined to enable the evaluation of success of each objective in the structured decision.

Table 1. Evaluation example from the options evaluation workshop (Hovdebo *et al* 2012).

	Stakeholder						
Objective	Uranium city	Northern Saskatchewan environmental quality Committee	Saskatchewan Ministry of Environment	Canadian Nuclear Safety Commission	Other federal	Cameco A	Cameco B
This option will protect the safety and health of local people	Agree	Disagree	Disagree	Disagree	Neutral	Neutral	Neutral
This option will protect fish and animals within the Beaverlodge mine area	Disagree	Disagree	Disagree	Neutral	Disagree	Disagree	—
This option will improve water quality near the mine area	Agree	Agree	Neutral	Agree	Agree	Agree	—
This option will improve recovery times of Beaverlodge Lake and downstream water bodies	—	Disagree	Disagree	Disagree	Disagree	Strongly disagree	—
This option will allow traditional use of land and water in the area	Disagree	Disagree	Disagree	—	—	—	—
This option will present good opportunities for local businesses and workers	Agree	Disagree	Agree	—	—	Disagree	—
This option will fit into the local landsacpe	Neutral	Disagree	Neutral	—	—	Agree	—
This option's implementation risks and short-term impacts will be acceptable	—	Neutral	Agree	—	Agree	Agree	Neutral
This option will be technically feasible	—	Agree	Agree	Agree	Agree	Agree	Agree
This option will be reliable over the long term	—	Neutral	Agree	Agree	Agree	Agree	Agree
This option meets the standard of good mine closure practice elsewhere	—	Disagree	Agree	Agree	Agree	Agree	Agree
This option will meet applicable provincial and federal regulations	—	Disagree	Neutral	Neutral	Neutral	—	—
This option will allow the site to be handed over to institutional control	—	Disagree	Agree	Neutral	—	—	Agree
This option will be a good use of public funds	Neutral	Disagree	Disagree	Agree	Agree	Neutral	Neutral

Figure 3. Objectives hierarchy.

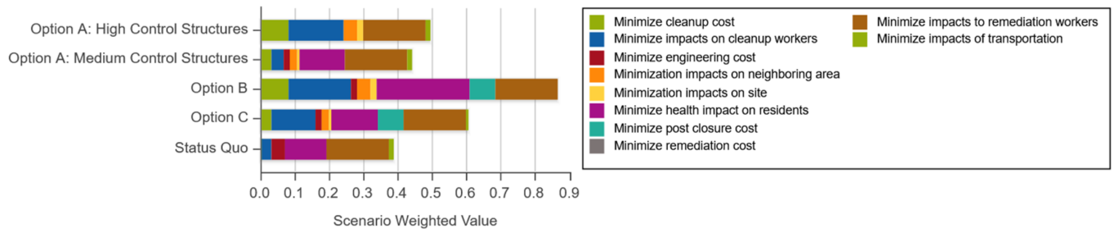

Figure 4. Consequence chart.

The decision analysis options in GiSdT were as follows:

- 'Option A'[11]:
  * 'Status Quo' (existing state of the drainage tunnel; no additional structures or measures).
  * 'Medium control structures' (clean-up of the clogged perforated drainage collection tubes in the drainage tunnel—performed in 2018 and 2019).
  * 'High control structures' (additional structures around the site for preventing background water infiltration into the mill tailings and beneath shales, marls, sandstones and conglomerates, which also slide together with the mill tailings; regular clean-up of the clogged drainage collection tubes will be needed).
- 'Option B' includes the removal of mill tailings from the Borst site and disposal in the mine pits.
- 'Option C' includes the total removal of mill tailings from the Borst and disposal on the Jazbec site.

Evaluation of the performance of the options was made using a consequence table and Bayesian network (Neptune and Company Inc 2017). The consequence table approach (figure 4) indicated that additional control structures improve the performance of option A—status Quo. The high control structures option is better than the medium control structures option. Option B as the best one.

The Bayesian network approach involved building a conceptual model to define causal links of the decision analysis model as shown in figure 5.

The Bayesian network evaluation indicated similar results as the consequence table approach. However, the introduction of the probabilities of the processes and the objectives indicators which measure objectives' success connected with each option reduces the differences between them. The status Quo and other two sub-options of A are valued relatively better compared to the consequence table approach (see figure 4) and may not be disregarded when making decisions.

[11] It should be noted that Option A is extended compared to what was considered using the DEXi decision analysis model. Options B and C, despite they are not actual any longer, were used in this decision analysis for the purpose of comparing DEXi and GiSdT.

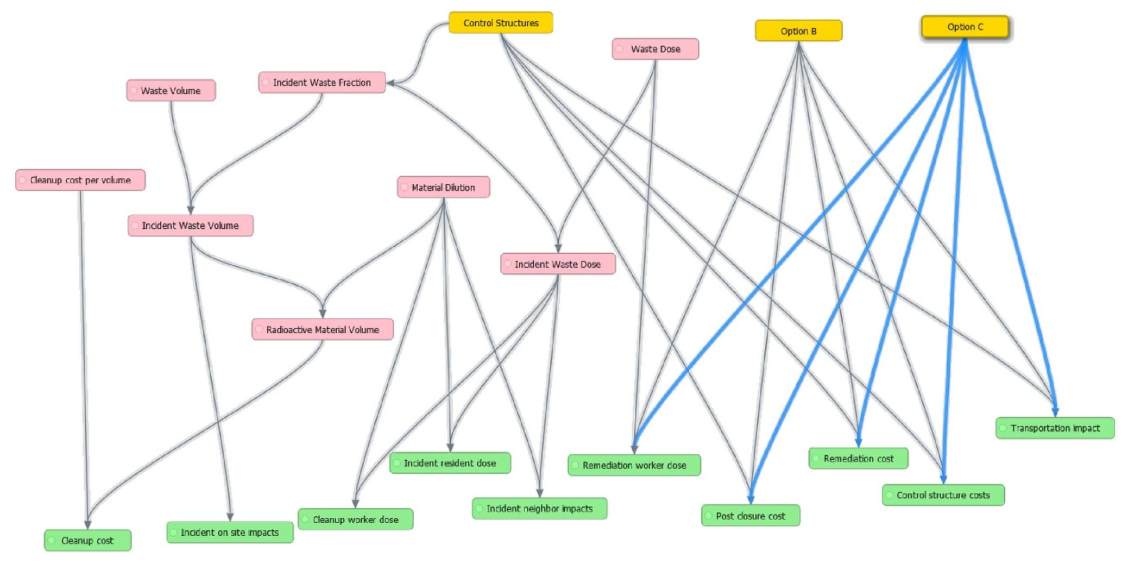

Figure 5. Bayesian network; yellow = options; pink = processes; and green = objectives indicators.

3.1.3. Case study 3: Kepkensberg/Tessenderlo

Different models and tools have been tested (AMBER, GoldSim, NORMALYSA, PC-CREAM08, PRG-DCC calculator, and RESRAD-OFFSITE). While the models showed some differences in their quantitative results for the end-points of the calculations—e.g. due to different assumptions regarding default values of parameters—they provided a fairly good qualitative agreement, as these differences were inside one order of magnitude. The radiological dose assessments as input for in the decision-making process was, thus, rather consistent regardless of the model applied. Details could be found in (Pepin *et al* 2022) in this special issue.

In the context of regulatory decision-making, the results of the radiological RA show that the annual dose limit of 1 mSv yr^{-1} in a planned exposure situation as the permitted dose is unlikely to be exceeded. It can, therefore, be concluded that these results support the hypothesis that it is acceptable from the regulatory point of view to dispose of the Winterbeek remediated sediment in the Kepkensberg sludge basin. However, the imperative of remediation should always be to implement best available, reasonable option, i.e. to strive for the least damageable one from all different aspects, not only radiological (ALARA).

Radiation is generally subjectively perceived as a higher risk compared to other hazards; however, this is often not the case. Objectively assessing the magnitude of the dose impact provides public reassurance regarding the radiological aspects of the contamination and allows for a proper and objective balance evaluation of radiological risk with relative to all other factors affecting decision-making in a remediation process. For the remediation of the Tessenderlo site, the relatively moderate dose impact confirms the appropriateness of the approach taken, where the chemical components of the contamination and the ecological restoration of the river formed the basis for the decision-making process.

3.2. Findings of the overview of the elements of figure 1(b) in selected case studies

The Beaverlodge case study is closest to the desired level of integrating decision analysis and RA with active and effective participation of stakeholders. It covers all the elements of a participative, deliberative approach, as presented in figure 1(b). This case study could serve as a reference for other situations where remediation of NORM or other types of nuclear legacy sites is needed.

The Slovenian case study (RŽV) reveals a situation that is closer to figure 1(a) than figure 1(b). The final decision is pending and it could be beneficial to take into account the decision analysis results described in this paper. According to the RŽV plan for 2021 (Klemenčič 2020), it is possible that the medium control structures option will be selected as final remediation option. Consideration of monitoring results for sliding velocities in 2020 and 2021, which need to be below 1.5 cm yr^{-1}, could add weight to the final decision. If, based on an evaluation of the monitoring data, the medium control structures option is found to be impractical (i.e. if it does not meet the 1.5 cm yr^{-1} criterion for sliding velocity), the high control structures option could be considered as a potentially feasible final remedial option. In such a situation, it seems reasonable to also reconsider options B and C, since both DEXi and GiSdT indicate that these options perform better than option A (see figures 4 and 6). As highlighted in the Beaverlodge case, in considering the possible remedial options for RŽV, a possible next step could be to communicate these decision analysis

Attribute	A - Existing state	B - Mine pits	C - Jazbec site
OPTION_SUITABILITY	not_suitable	suitable	less_suitable
ENVIRONMENTAL PROTECTION	less-suitable	excellent	suitable
RADIOACTIVITY	not-suitable	suitable	less-suitable
WASTE PILE STABILITY	not-suitable	suitable	less-suitable
DEGRADATION	high	medium	high
EVENTS	low	low	low
EROSION	high	low	medium
TRANSPORT OF RADIONUCLIDES	high	medium	medium
WATER	high	medium	medium
INTRUSION	medium	low	medium
LAND-USE	suitable	suitable	suitable
SETTLEMENTS	suitable	suitable	suitable
RECREATION	less-suitable	suitable	less-suitable
RATIONALITY	not-suitable	less-suitable	not-suitable
THRIFTINESS	high	medium	high
MONITORING-MAINTENANCE	high	low	high
INTERVENTIONS	high	medium	high
EXPOSURES	not-suitable	less-suitable	less-suitable
OPTION STABILISATION	low	high	high
DIGGING	low	high	high
TRANSPORT	low	high	high
SOLIDIFICATION	low	high	high
CLEAN-UP	high	low	medium
WASTE SITE	medium	low	medium
NEIGHBORING AREA	high	low	medium

Figure 6. Evaluation results of the RŽV.

results in an open and participative manner to the decision makers (SNSA, MESP, MI, ARWM) and stakeholders (e.g. the municipality administration and farmers in the surroundings of the site) aiming to reach consensus on which remedial option is to be implemented, possibly following the approach in figure 1(b).

In the Belgian case study, radiation protection aspects formed only a minor part of the overall decision-making context (see Pepin *et al* 2022 in this special issue). The remediation process for the Winterbeek River was instead driven, on the one hand, by considerations related to the non-radioactive contamination (chloride and heavy metals) and, on the other, by considerations related to integrated water management and restoration of the ecological quality of the marshland area. Protection of the specific biota living in that area prevented, for instance, the application of intrusive remediation techniques (such as ground excavation) in the ecologically sensitive parts of the contaminated area. All these factors were discussed and weighed within a multi-agency committee with participation of different national and local authorities or institutes in charge of, for example, environmental protection, water management, nature conservation, and radiation protection.

An overview evaluating how well each of the three case studies aligned with the elements of more participative, deliberative approaches to decision analysis (depicted in figure 1(b)) is summarized in table 2.

4. Discussion

The key lessons in the area of risk-informed decision-making come from the Beaverlodge and the RŽV case studies, while the Kepkensberg case study demonstrates overarching goal of achieving ecological restoration of the marshland area and of integrated water management, where radiation protection aspects formed only a minor part of the overall considerations. The first of these cases demonstrates the approach, methods, and specificities regarding effective stakeholder engagement, as discussed in the IAEA's MODARIA I and II programmes, and the second case shows the transparent application of computer-aided decision analysis tools as support to pending final decision. Both case studies show that methods that genuinely seek stakeholder inputs need a firm commitment to engagement, transparency, and building trust among the stakeholders. The specific elements include:

- a clear and documented understanding of the decision-aiding process, including the participants, roles, and responsibilities. This has been done in case study 1 (Beaverlodge), but not in case study 2 (RŽV). Therefore, it is reasonable to conclude that omitting to make the decision process for RŽV open and participatory makes final decision uncertain and delayed;
- extensive consultation on the options to be evaluated. Again, the Beaverlodge case study shows success also with regard to identifying and evaluating remediation options in a wide participation and consultation with stakeholders, while such consultation in the case of RŽV was missing so far. It remains to be seen whether this will change in the future;
- sufficient time and financial resources for the supporting studies. Differences between case study 1 and case study 2 are conceptually same as above; and

Table 2. Overview of the elements of figure 1(b) in selected case studies.

Elements of figure 1(b) / Case Studies	Communication	Pre-decision phase		Decision-making phase		Post-decision phase	
	Stakeholder participation, inclusive consideration of factors and interests	Concerns and motivation for decision-making	Framework of considerations	Wider context of the decision problem, options for solving a problem	Decision analysis provides the need for supporting RA/impact assessment and other supporting studies. RA should follow the decision context—fit for purpose	Post-decision considerations	Implementation of selected option and follow-up
Beaverlodge, Canada	Yes (continuous stakeholder participation with transparent iteration and looping of key information throughout the decision-making process)	Yes (consideration of concerns and motivation for decision-making, problem definition, clarification of objectives)	Yes (an iterative process which starts with pre-decision considerations, continues with decision analysis, and ends with the decision on implementation option)	Yes (aiming to provide guidance for selecting best implementation option)	Yes (according to the results of stakeholder participation and decision analysis, which reveals the need for other supporting studies in addition to risk/impact assessment)	Yes (knowledge management, regular auditing of the effectiveness of implemented option, and looping back to stakeholder participation with confidence building)	Yes (follow-up and transparent and inclusive auditing of the success of implemented option are important contributors to public confidence)
Uranium mill tailings RŽV, Slovenia	Partly (continuous stakeholder participation is not established)	Partly (regulatory compliance is the key motivation)	Limited (regulatory requirements form the basis and framework of considerations)	Limited (regulatory requirements form the basis and framework of considerations)	On-going (decision analysis is to be further extended; participation of other stakeholders is envisaged)	Not applicable (final decision has not been made yet)	Not applicable (final decision has not been made yet)
Kepkensberg (Tessenderlo area), Belgium	Remediation was required to comply with the overarching goal of achieving ecological restoration of the marshland area and of integrated water management, including the control of flooding in the area. In this context, radiation protection aspects formed only a minor part of the overall considerations. The factors were discussed and weighed within a multi-agency committee with participation of different national and local authorities in charge of, for example, environmental protection, water management, nature conservation, and radiation protection.						

- participation by regulatory and other expert groups in the design and review of the supporting studies. This participation in the RŽV case study was formal and limited to regulatory requirements (i.e. according to legislation).

In dealing with multiple stakeholder groups, one must be prepared to 'speak their language' literally and metaphorically. That necessarily means that there can be no one decision-aiding method that is universally applicable. For example, the evaluation questions used in this case are likely to need extensive re-working for any other project. However, the basic philosophy of fully engaging stakeholders in 'plain English' dialogue, built on a foundation of rigorous decision analysis, has been successfully applied to other cases.

Lessons learnt regarding two decision analysis tools that were used in the RŽV case study are described here. Both DEXi and GiSdT are based on breaking and organizing the main goal or an objective of a decision problem into sub-problems, and consequently, creating a hierarchically organized tree of objectives (in GiSdT) or attributes (in DEXi). The DEXi evaluation is based on the tree of attributes that are aggregated into the main decision attribute for each option. Each attribute describes specific characteristic or performance of the options; nodes in the tree synthesise these specific characteristics/performances towards the main decision attribute (Bohanec 2020). GiSdT evaluation focuses on how the preference-weighed objectives of the decision problem are met by each option. Importantly, for GiSdT, the values and preferences of the interested parties need to be structured before the options become defined. Both DEXi and GiSdT use categorical scales and continuous measures. Additionally, the GiSdT Bayesian network evaluation enables the introduction of uncertainty of processes through the determination of discrete probabilities. The final step in GiSdT is the adaptive management step. DEXi does not directly include such a follow-up step after the decision is made and implemented. Instead, an iterative re-evaluation of the implemented option can be done using DEXi by introducing additional options and modifying the decision model accordingly.

More general discussion of how these methods improve the quality of decision-making may be found in Gregory *et al* (2013) and Spetzler *et al* (2016).

Regarding the application of different RA models and tools for the Belgian case study, the findings are presented and widely discussed in Pepin *et al* (2022) in this special issue.

Proposals for modelling improvements to better fit decision needs and contexts are given below in the form of statements and questions that should be considered on a case-by-case basis Griffault *et al* 2022, Thorne *et al* 2022). The proposals also come from the experience gained within the case study 3:

- Modellers should have possibilities to facilitate open communication with the decision makers and other stakeholders on issues that need to be known and identified through decision analysis and prior to risk modelling. Regarding radiological modelling in case study 3 (Tessenderlo site) this communication was limited and was concentrated on communication with Federal Agency for Nuclear Control.
- Conceptual modelling should be open to questions, proposals, views, and standpoints of the parties involved in problem-solving within the decision context. The experience from case study 3 is similar as above: assessors/analysts communicated among themselves and with Federal Agency for Nuclear Control.
- Scenarios should meet the needs and expectations of the decision makers. To achieve this, the decision makers and other stakeholders should be involved in the development of the assessment context, as well as other key components of risk modelling, such as conceptual model development, modelling scenarios to fit specific concerns and needs, and other components, as relevant. Since it was about a regulatory decision the needs and expectations considered were those from Federal Agency for Nuclear Control.
- Scenarios should clearly consider management options to be considered, compared, and finalized (e.g. engineered features and arrangements) and should facilitate optimization in support of decisions. Case study 3 considered one option only.
- Calculation timeframes should reflect decision needs. Scenarios should clearly present related epistemological modelling uncertainties, for example, pertaining to expected or assumed long-term societal and environmental changes, possible exposure situations, human behaviour, food availability and nutrition habits, non-work-related and work-related activities for time frames beyond several hundreds of years, and others, as relevant. The level of uncertainty around such factors would contribute to the overall confidence in the RAs. Modelling timeframes were not thoroughly examined and consulted in case study 3 so it remains to pay more attention to this issue in the future.
- Does modelling adequately represent the decision contexts for the final arrangement of the sites (end state) pertaining to implemented the remediation and management option? How is the end state determined?
- How to evaluate success of the modelling? Who are evaluators when the modelling and RA process follows the framework of figure 1(b)? Which indicators and measures are best in such evaluation and how much do they support credibility of modelling results—are they in any relation with objectives set in the assessment context and in a decision analysis framework? Should decision context and decision needs provide specific

measures of success? Should the measures include trust and respect among stakeholders throughout the process?

5. Conclusion

The international community has come a long way in developing a consensus that the remediation and management of NORM and other types of nuclear legacy sites will benefit from the use of the framework for risk-informed decision-making. Such a framework has been developed primarily in MODARIA I and II Programmes. In addition, several other programmes, networks, and projects have also contributed to this consensus; for example, ENVIRONET—DERES, RICOMET, NEA EGLM, TERRITORIES, and CONFIDENCE. New knowledge and lessons learnt through all these research and collaboration efforts have led to a number of recommendations for future work. It is proposed that these recommendations are considered for implementation in the follow up to the MODARIA II programme (Harmonized MEthods for Radiological Environmental Impact Assessment (MEREIA)), perhaps by means of specific case studies covering, for instance, decision concepts as captured in figure 1(b), integration of decisions, RA, improvements to model-data comparisons and their role to support the decision analysis, and related topics. If such integrated and targeted approach to MEREIA were also to include formal stakeholder engagement in decision analysis, it would be a strong contribution to objective, robust, and transparent decision-making not only for radiation protection (e.g. in support of optimization of protection and safety) but also for other areas where human and environmental impacts are of concern.

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Conflicts of interest

Authors and co-authors have no conflict(s) of interest with regard to submitting this article.

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