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Integrated Approaches for the Management of Environmental Site Remediation Processes: A Baseline Report

INTEGRATED APPROACHES FOR THE MANAGEMENT OF ENVIRONMENTAL SITE REMEDIATION PROCESSES: A BASELINE REPORT

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INTEGRATED APPROACHES FOR THE MANAGEMENT OF ENVIRONMENTAL SITE REMEDIATION PROCESSES: A BASELINE REPORT

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FOREWORD

Environmental remediation projects can be very complex endeavours that involve taking many different variables into consideration. Some variables are tangible and can be quantified, such as cost and risk, while others are more subjective and deal with preferences and perceptions. Decisions will also affect different groups of stakeholders that can include not only the communities living adjacent to an affected area, but also those that are not directly affected but that will eventually be part of the solution. For example, the waste resulting from an adopted remediation approach may be disposed of in a location different from the one being remediated.

The very nature of the situation resulting in the contamination of the land has an influence on the overall decision making process. For example, if remediation results from a past activity when regulatory requirements were not in place or were not aligned with current international standards — the case for legacy sites — or if the process results from a radiological or nuclear accident, then stakeholder attitudes can vary from fear to frustration and anger greatly impacting trust in authorities, which could in turn have negative impacts on the decision making process.

These aspects were raised in the International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes, organized by the IAEA and held in Madrid in 2016. The conference recognized that integrating public engagement into decision making on environmental remediation, particularly concerning desired end states (including reference levels), was extremely complex. To this end, attention was called to the fact that to reach a sustainable end state, governments and implementers need to engage stakeholders in the decision making process and to respond to societal challenges.

To address those issues a project as part of the IAEA's Network on Environmental Management and Remediation was designed and is currently being implemented. The overarching objective of the Management Systems Supporting Environmental Remediation project, known as the MAESTRI project, is to develop a structured framework that considers in an integrated manner the different dimensions and activities relevant to the proper management of sites contaminated by ongoing or past activities (including accidents), to bring them to sustainable end states suitable for beneficial use. For this purpose, the project will provide practical guidance for developing a structured framework for the integrated management of contaminated sites. This includes (i) a holistic perspective, taking into account the plurality of dimensions and values to be considered; (ii) the evaluation of the sustainability of site management options, namely the social, economic and environmental aspects; and (iii) a transparent, consistent, comprehensive and inclusive decision making process.

This publication is intended to provide Member States, relevant organizations, practitioners and policy and decision makers with an overview of the frameworks, approaches and tools currently used in the scope of decision making regarding environmental remediation projects. The publication also aims to identify gaps in existing knowledge and tools so that the MAESTRI project can contribute to improving the decision making mechanisms currently used in the scope of environmental remediation projects.

The IAEA officer responsible for this publication was H. Monken-Fernandes of the Division of Nuclear Fuel Cycle and Waste Management.

EDITORIAL NOTE

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1. INTRODUCTION

1.1 BACKGROUND

The operation of any industrial facility has the potential to cause environmental impacts that will imply various levels of risks to humans and the environment. In the past, the environmental impacts were considered as externalities (marginal costs) in project planning and implementation. As a result, considerable amounts of land have been contaminated, and the associated risks - to members of the public warranted some sort of environmental intervention. The adoption of a life cycle thinking, internalization of environmental costs in project feasibility studies, the existence of stricter regulations and the demand for establishment of trust funds to shoulder the costs of possible environmental interventions in the -post-operational phase of industrial facilities are some of the features that have been applied over the last decades and are in place in the scope of the licensing of industrial operations and to a large extent derive from the lessons learned with the mistakes from the past.

Dealing with radioactively contaminated sites goes far beyond reducing radiological risks through implementing specific technologies/techniques. Technical, scientific, economic and social dimensions need to be included in the decision process and finding the right balance between all these dimensions has proven to be a very difficult task. The reason for this complexity is the need to deal simultaneously with several potentially diverging objectives, values and expectations. At the same time, assessments need to include quantifiable variables of objective nature and variables of subjective nature that cannot be easily quantified. The latter have turned out to be a considerable driving force behind the decision-making process in many countries.

The IAEA led Conference on Decommissioning and Environmental Remediation that has taken place in 2016 in Madrid made a clear call for international support in having in place mechanisms for decision-making to be used both in the decommissioning of facilities and remediation of contaminated sites [1]. The need for having in place a framework to be used in the remediation of nuclear sites, which would lead to sustainable solutions for the situations being dealt with, has been also recognized [2]. In general, a framework is a practical or conceptual structure intended to serve as a support or guide for the establishment of an evaluation or decision-making procedure to be used in a particular domain and a particular national context. Research projects conducted under the auspices of the EC-H2020 framework further emphasized that it was necessary to consider ethical, social, and cultural values in decision-making processes [3]. In this context, the old logic of ‘Decide-Announce-Defend’, i.e., a way of dealing with a situation or problem, is no longer seen as a valid or effective approach.

With the above in mind, the IAEA-ENVIRONET has been working in close cooperation with different social sciences and humanities experts to integrate the inputs coming from these areas into the established competencies in the realm of the engineering and natural sciences applied to issues related to environmental remediation. Such cooperation has been examined and discussed in different annual gatherings of the ENVIRONET community.

In the 2018 Annual Meeting of ENVIRONET, participants suggested that the IAEA ENVIRONET could develop a dedicated project to support the decision-making process in the scope of Environmental Remediation (ER) works and consider expanding the concept of ER to a broader approach represented by Environmental Management (EM). It has been emphasized that remediation activities needed to be considered in a life-cycle perspective, taking due account of sustainability principles.

In 2019 the MAESTRI project (Management Systems Supporting Environmental Remediation Projects) was launched to develop a structured framework that considers, in an integrated manner, the different dimensions and activities relevant to the proper management of sites contaminated by ongoing or past activities (including accidents), with a view of bringing them to sustainable end-states suitable for beneficial use. MAESTRI’s vision is to ‘transform a liability into an asset’, in other words, transform a problem into an opportunity. By doing so, MAESTRI proposes to broaden the scope of ER which is defined in the IAEA Safety Glossary [4] as “any measures that may be carried out to reduce the radiation exposure due to existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans".

The MAESTRI project aims at providing practical guidance for developing a structured framework to the integrated management of contaminated sites, that includes:

- A holistic perspective, taking into account the plurality of dimensions and values to be considered;
- The evaluation of the sustainability of site management options, i.e., the social, economic and environmental aspects; and
- A transparent, consistent, comprehensive and inclusive decision-making process.

The project recognizes that participation of relevant social actors needs to be an integral part of the site management process, leading to better decision process and enhanced human well-being. It also provides a platform for sharing practical experiences among Member States (MS) on related aspects of the environmental management of contaminated sites.

The first step in MAESTRI is the elaboration of this 'Baseline Report', i.e., a high-level publication aiming at reviewing the frameworks, approaches and tools used in the decision-making process related to the remediation of contaminated sites. It also identifies gaps and articulates a series of proposals to be used in the scope of decision-making regarding environmental remediation projects.

1.2 OBJECTIVE

The primary objective of this report is to provide an overview of frameworks, approaches and tools currently used in the scope of decision-making regarding environmental remediation projects. An associated objective is to identify gaps in existing knowledge and tools and make available to the MAESTRI working groups an analysis of ways to improve the mechanisms that are currently used in the decision-making in the scope of ER projects. MAESTRI has a clear vision that such decision processes need to be more comprehensive and aligned with sustainability objectives. Those mechanisms would consider environmental remediation into the broader outreach of environmental management in such a way that all the stages and dimensions relevant to this process (technical, social, environmental, economic) are brought together. This analysis relies on existing guidance documents and literature as well as the experience and lessons learned from past or ongoing environmental remediation projects.

MAESTRI approaches are also linked with the principles of the circular economy. In the particular case of remediation, it aligns with the vision of re-thinking remediation from a limited perspective of harm reduction to one that involves value generation that can be translated into bringing land as much as possible into recreational, commercial, agricultural purposes and to natural ecological systems as appropriate [5].

1.3 SCOPE

This publication reviews and discusses the state of the art in decision-making for environmental remediation, highlighting challenges for effective implementation, particularly considering non-technical aspects and the necessary means to these integrated into the overall process. Past and ongoing initiatives, environmental remediation projects, research and case studies are reviewed to answer the following questions:

- What are the objectives of the ER projects?
- How have decision-making processes been conducted?
- What were the main challenges encountered in the decision-making process?

- What were the consequences of the decisions, also in the long term (e.g., residual levels of contamination, waste generation, effectiveness in the long term of the remediation solution, long term support from the community)?
- Which recommendations can be formulated for the improvement of ER decision processes?

1.4 STRUCTURE

Section 2 of this document introduces and provides arguments for an environmental management approach to radioactively contaminated sites. These arguments are further elaborated in Sections 3 and 4. Among others, social, economic and ethical aspects are highlighted, as well as the essential role of stakeholder involvement.

Decision-making in the scope of environmental remediation also requires tools and framework allowing for an inclusive and transparent process, which takes due account of all the important social, technical, environmental and economic aspects. Section 5 includes a review of decision-making tools and frameworks used both in the nuclear and non-nuclear environmental remediation areas.

Among the frameworks guiding decision-making, sustainability has gained increasing importance as an overarching framework for holistic decisions on environmental problems. For this reason, Section 6 is dedicated to the sustainability of environmental management. Key concepts, conceptual tools as well as novel approaches are described here.

Sections 2 to 5 illustrate key concepts, frameworks and approaches that can be used to support decisions in the scope of environmental management. In practice, environmental remediation decision-makers and implementers are often challenged by questions such as: How to include all important dimensions in the evaluation of options in a structured analytical way? How to ensure an inclusive, transparent and equitable process? Special attention is given to multi-criteria decision-analysis as this can provide for the inclusion of multiple values and dimensions in decision-making, with due attention to ethical considerations, e.g., who is affected and in which way by applying or not applying a particular remediation strategy?

Several case studies are included in Appendices. They illustrate decision-making challenges and gaps encountered, as well as lessons learned from past or ongoing environmental remediation projects, from the social, ethical and economic perspectives. These cases are the Wismut remediation project (Germany), remediation on the Uranium mines at South Alligator (Australia), remediation of Arsenic-rich tailings from a Tungsten mine (Portugal), the Malvezy site in France, and the remediation of large contaminated off-site areas following the Fukushima Daichi nuclear accident (Japan). The findings from these case studies serve for illustrating particular arguments in Sections 2 and 6.

An important feature of this publication is that ‘take-away messages’ are provided at the end of most (sub)sections in an effort to call attention to important considerations that capture key points discussed in the scope of that particular sub-section.

2. MOVING TOWARDS ENVIRONMENTAL MANAGEMENT

Environmental management is a dynamic concept that has been introduced in the 1970s as a 'problem-solving field' and has evolved from a top-down technocratic approach to one where the 'public demand for accountability and consultation' and the social, ethical and economic issues are increasingly in focus [6]. It is now recognized that environmental management requires inputs from a variety of disciplines, including social sciences, and a plurality of stakeholders, including citizens. Currently, environmental management could be seen to encompass "actual decisions and actions concerning policy and practice regarding how resources and the environment are appraised, protected, allocated, developed, used, rehabilitated, remediated, and restored" [7]. In this sense, environmental management is delineated as a decision-making system that integrates the complexity of ecological systems and the complexity of interdependent human organizational and institutional systems[1]. With this shift towards an integrated, adaptive and system-based approach, a move away from a reductionist, command and control management is made.

According to [6] environmental management "seeks to improve environmental stewardship by integrating ecology, policymaking, planning and social development". Its goals include sustaining/improving existing resources; preventing and resolving environmental problems; establishing environmental norms and institutions; analysing threats, identifying opportunities and improving 'quality of life' while identifying new technology; practices, policies, and procedures undertaken to comply with local, state and/or federal environmental legislation.

In the context of radioactively contaminated sites, environmental management faces societal challenges and visions that are common to other types of contamination, as well as specific ones. These include among others, potentially large-scale, long-lasting environmental contamination; unequal distribution of risks and benefits; contrasting views and perceptions of radiological risks by experts and affected populations, and the risk of stigmatization of both people and goods from affected areas [8-14]. Studies carried out in the aftermath of the Chernobyl and Fukushima nuclear accidents, as well as those focusing on the remediation of legacy sites highlight the importance of a holistic approach. This is translated by an environmental management framework that explicitly includes the societal dimensions in decision-making and enables cooperation of local actors among themselves and with other relevant actors and networks [3, 15]. From this perspective, environmental remediation as applied to radioactively contaminated sites has to move from a radiological risk-based perspective, centred on dose reduction, to a wider, multifaceted and interdisciplinary framework encompassing also social, economic and ethical considerations. A suitable overarching framework accounting for all these dimensions is that of sustainability, in line with the United Nations Sustainable Development Goals[2].

It could be argued that optimization in the scope of Radiation Protection translated by the ALARA (**A**s **L**ow **A**s **R**easonably **A**chievable) principle already contemplates some of the dimensions alluded above, as the social and economic aspects need to be considered in the overall decision process related to the remediation of a contaminated site. In association with Justification ("do more good than harm"), these two principles together provide the basis for a fair, reasonable and consistent process for decisions related to the remediation of a contaminated site. The reality, however, demonstrates that the international community is still struggling to have in place a functional framework that can support,

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[1] According to ISO14001, an environmental management system (EMS) is the part of the management system of an organization used to manage environmental aspects, fulfil compliance obligations, and address risks and opportunities. Environmental aspects refer to activities or products or services that interact or can interact with the environment (air, water, land, natural resources, flora, fauna, humans and their interrelationships). https://www.iso.org/obp/ui/#iso:std:iso:14005:ed-2:v1:en

[2] The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, formulated 17 Sustainable Development Goals (SDGs), calling for urgent call by all countries in a global partnership.

among others, the decisions on the so-called reference levels to be determined in the context of existing exposure situations. A Reference Level is to be taken as [4] *"The level of dose, risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented"*.

Consideration of the wider social, economic and environmental factors in the context of sustainability may inform what is reasonable and achievable.

Overall, the decision on the extent of remediation to be put in place in a contaminated site after a nuclear or radiological accident or in a legacy site is a rather complex process. Key aspects are the future use of the site, the site end-state, the residual level of contamination (which is, in turn, connected with the choice of reference levels), the selection of remediation technology, the timeframe for remediation implementation, the sustainability of chosen strategies, the consideration of social, economic and environmental impacts in affected areas and communities, the transparency of the process and the participation of different stakeholders. These aspects require a holistic, integrated multi-criteria framework that is better accommodated in the broader context of environmental management. As a result, this publication maintains the use of the term environmental remediation, but it conveys the message that it would be appropriate if it could embrace a more inclusive thinking aligned with the objectives of environmental management.

3. DECISION-MAKING IN ENVIRONMENTAL MANAGEMENT

When discussing decision-making considerations for environmental remediation, it is crucial to understand the complexity of these processes.

3.1. GENERAL CONSIDERATIONS

First, decision-making is often perceived as a rational process. However, even though decision-makers try to be rational, they are challenged by the complexity of the situation) [16]. Furthermore, human beings are inherently ‘not entirely rational’, although they intend to be. For this reason, scholars from various scientific disciplines, as well as managers, policymakers and practitioners have attempted to structure decision-making in order to shape decision-making processes that are ‘rational up to a certain point’.

Second, decision-making is often made in disorder and surrounded by uncertainty and complexity. According to [17], this is due to the fact that: “technologies are changing and poorly understood; alliances, preferences and perceptions are changing; problems, solutions, ideas, people and outcomes are mixed together in a way that makes interpretation uncertain and their connections unclear” (p. 168).

Finally, decision-making is influenced by personal beliefs i.e., by the social and cultural contexts.

All the aforementioned aspects are also true for decision-making in the scope of environmental remediation.

Various decision-making theories, methods (practical expressions of theories) and tools, e.g., software, have been designed and implemented to structure decision-making processes, address their complexity and increase their quality.

In practice, if decisions rely only on technical input and do not take into consideration the social and ethical implications, they may lead to ineffective and contested decisions. Decision processes have also to ensure, to the extent possible, opportunities for stakeholder participation, deliberation and joint problem solving. This is particularly relevant for environmental remediation.

Decision methods need to provide for an ‘organized, inclusive, and transparent approach to understanding complex problems and generating and evaluating creative alternatives’ [18]. For instance, ‘multi-criteria stakeholder mapping’ highlights the different decision options associated with different socio-political perspectives [19]. Deliberative mapping [20] and the structured decision-making proposed in [18] bring into focus analytic–deliberative participatory appraisal methods. Finally, Social Multi-Criteria Evaluation [21] further emphasizes the need to include equity considerations in decision-making and uses methods from both natural and social-science methods to define the problem, the evaluation criteria and the decision options.

According to [22], traditional decision analysis can be classified into:

- Descriptive, which describes how people make decisions;
- Normative, which advocates how rational decisions ought to be made;
- Prescriptive, which seeks to combine descriptive and normative elements, in order to reflect the practical needs and constraints of the specific decision context.

A further differentiation, which is of particular interest in MAESTRI, can be made between decision frameworks developed in the context of a specific discipline and those aiming at multi- or trans-disciplinary approaches. For instance, Social Multi-Criteria Evaluation (as will be discussed later in this publication) was developed to integrate a plurality of disciplines and sources of knowledge; Cost-Benefit-Analysis was developed with an economic perspective, while Life-Cycle-Assessment reflects an environmental, ecological perspective.

3.2. SOCIAL, ECONOMIC AND ETHICAL ASPECTS

As highlighted above, both research and practice reflect a shift towards a more comprehensive evaluation of environmental management options that goes beyond the radiological impact, technical feasibility and direct costs. Such evaluations would account for the inclusion of the social, cultural, political, environmental and economic impacts into decision making processes.

It is also important to recognize that decisions made will always involve value judgments. The definition provided by the IAEA to environmental remediation focuses for on the reduction of doses in the context of existing exposure situations; stipulating that the intended dose reduction has to be justified and optimized. In particular, in the process of optimization and justification of remediation in the scope of existing exposure situations, reference levels are to be established and, any number in the range of 1 – 20 mSv/y could be considered as acceptable [23]. However, the interpretation of how inclusive the arguments used for justification needs to be, and what optimization entails, have tremendous effects on the decision-making process and, of course, on the final decision. This will depend largely on technical, as well as non-technical aspects. One of the challenges in setting reference levels for remediation is that for planned exposure situations the dose limit conforms with the value of 1 mSv/y [24], which coincides with the lower end of the reference level range applicable to remediation.

3.2.1. Key considerations

The interlinkages between the technical, economic, environmental and social aspects of environmental remediation of radioactively contaminated sites, and the resulting societal challenges for environmental remediation projects have been highlighted in several studies [3, 15, 25, 26].

The aftermath of the Chernobyl accident, for instance, emphasized the importance of adopting a robust remediation strategy that takes into account not only the technical feasibility and radiological effectiveness, but also the economic and environmental aspects, as well as the social acceptability of the proposed strategy, ethical considerations, as well as the “spatial variation and the contrasting needs of people in urban, rural and industrial environments” [9]. Similarly, reviews of both the Chernobyl and Fukushima accidents stressed the importance of considering ethical aspects such as the distribution of risks and benefits and the respect of dignity and autonomy of populations [27, 28].

Remediation processes may have diverse social, environmental, ethical and economic, direct and indirect impacts [29]. For instance, remediation efforts made agricultural production possible in many areas affected by the Chernobyl accident, but implied additional costs compared to standard agricultural practices, as special crop cultivation practices had to be implemented [9]. As another example, the introduction of food monitoring programs and changes in husbandry practices after the accidents in Chernobyl and Fukushima ensured that production could continue, protecting the societal and economic interests of farming communities. Nevertheless, in the aftermath of the accident, the consumption, processing, and distribution of products originating from the affected areas experienced a decline. This decline can be attributed to the negative perceptions and concerns associated with the contamination caused by the accident, which affected the local agriculture and industry [9, 10].

Some remediation actions may provide benefits that go beyond dose reduction, such as provision of monitoring equipment, public information and engagement or access to medical support [9].

Potential negative consequences of remediation processes, on the health and wellbeing of the population or the sustainability of environmental remediation, may not be related to the remedial options per se, but to the insufficient consideration of social and ethical aspects as inputs to decision-making [29]. For instance, some environmental management options applied after the Chernobyl accident required subsidies from the state to avoid uncompetitive production costs, which weakened the local economy [29].

In the case of legacy sites, a major challenge is that most of these sites were created in circumstances in which there was no regulatory framework in place or if so, it did not comply with modern standards. The determination of the responsible party for the legacy sites, as well as the communication of risk to the public (e.g., related to dose magnitudes), are frequently highlighted as main challenges of the remediation and associated waste management at legacy sites [30]. Additional challenges that can be associated with legal, social and economic factors and that can cause uncertainties for experts, public and other stakeholders are outlined in [3] and [26].

These include:

- Lack of a legal and regulatory framework;
- Poor communication;
- Lack of engagement of stakeholders;
- Polluter not existing anymore;
- Cost of remediation;
- Meeting/maintenance of remediation goals in the scope of long-term stewardship;
- Different risk perceptions;
- The meaning of end state;
- The impact of remediation on the socio-economic development of the region;
- The justification of using specific models for radiological assessments;
- Health impact of remediation works;
- Protection of vulnerable groups [3].

The effective implementation of any environmental remediation strategy may depend significantly on how people make sense of risks and how they make decisions to accept or reject these risks. This is driven by a broad range of considerations, related to the process of decision-making, the impacts of remediation options, but also to the situation (e.g., what is the activity that generated the risk? is it a voluntary exposure? is the risk perceived as controllable? is the distribution of benefits and risks perceived as fair?). Process related aspects, such as the perceived fairness and inclusiveness of the decision-making process have also been shown to play an important role [25, 26]. Since societal priorities for risk mitigation activities may not align with those identified by technical expert groups, values attributed by affected stakeholders to the outcomes at stake must be identified and taken into account in remediation processes [31].

It is proposed in Ref. [32] that the theoretical concept of ‘dignified living conditions’ is adopted as the overall objective for post-emergency management. This refers to seven types of resources of a community and its individuals that are potentially affected and will need to be rebuilt after an accident:

- “Integrity and personal ability to act;
- The existence of conditions allowing people to satisfy their basic needs in an effective way;
- The ability to act with others;
- The ability of people to build meaning, personally and with others, to orient themselves and, in this perspective, to access reliable, meaningful, true information;
- The possibility for people to benefit from a fair and equitable institutional and political environment and to have an influence on it;
- Territorial rooting of individuals and communities;
- Symbolic and spiritual resources” [32].

Such considerations can also be found in the ethical principles of radiation protection, as formulated by the International Commission on Radiological Protection (ICRP), which highlights four core values that can serve as a practical tool in assessing environmental remediation interventions [33]:

- Beneficence/non-maleficence: promoting or doing good and avoiding doing harm;
- Prudence: making carefully considered decisions in situations characterized by uncertainty;
- Justice: fairness in the distribution of advantages and disadvantages or risks:
- Dignity: “the unconditional respect that every person deserves, irrespective of personal attributes or circumstances, with personal autonomy as a corollary” [33].

From this perspective, accountability, transparency, and inclusiveness are considered procedural values in the implementation of radiation protection measures.

It is also important to highlight that creating capabilities for citizens to monitor the contamination and follow-up the remediation process and its outcomes, can contribute to citizens’ better understanding of the impact of the overall situation on their own lives, reducing social uncertainties and empowering them to participate in decision-making processes and taking informed decisions [34]. It may also contribute to enhancing the confidence in governmental authorities if data independently acquired are in good agreement with data disclosed by official organizations.

Past reports, as well as the case studies included in this publication, confirm that the remediation strategies adopted, the cost and resources required, the waste management options, the radiological criteria, and the intended timescale for implementation may vary considerably depending on the non-technical factors [30]. Generalized recommendations that do not account for the local site-specific conditions can therefore result in inadequate decision making [23].

Budgets need to be realistic and include significant contingencies to compensate for the lack of detailed background information. As the Fukushima case study, in the appendix of this publication, suggests, while it is important to define clear criteria for setting boundaries for areas requiring remediation, it is also important to consider the actual situation when realistic data becomes available. The method of drawing these boundaries will have a significant impact on the cost of decontamination, the area to be covered, and the future of the residents living there.

The importance of including non-technical considerations in environmental management projects is increasingly coming to the fore also in the context of policies and frameworks for sustainable remediation. These recognize the importance of the three pillars of society, environment and economy, but also the ethical challenges that arise from conflicts between these pillars, as well as the sustainable development goals (SDGs) themselves. The need to balance societal, economic and health aspects, adds additional ethical dimensions to remediation, both with respect to how the decisions are carried out and how the various impacts are assessed.

While significant effort has been dedicated to the radiological, environmental and economic analysis of remediation options (e.g. [23, 35, 36]), there is a need for clearer descriptions and operationalization of the social and ethical impacts with a view towards including these aspects in a structured way into decision making. Some insights that may be useful in that respect are provided in Section 5, drawing on the rich experience from nuclear and non-nuclear domains. Section 5, on sustainable remediation also discusses frameworks that aim at providing a comprehensive description of non-technical aspects, as well as operational indicators.

3.2.2. Take-away for social, economic and ethical aspects

Considering the above discussions some generic ‘takeaway’ messages can be proposed:

- There are inherent value judgments in all decisions, including those for setting up reference levels or the application of the justification and optimization principles;
- Social, economic, environmental and ethical dimensions of environmental remediation projects are linked to the particular local, regional and national contexts;
- Participation of stakeholders including the public, is a key success factor for effective decision-making;
- Particular attention has to be given to understanding and caring for the needs of groups that are vulnerable (e.g., socially disadvantaged or having specific health risks);
- Trade-offs between the three pillars of sustainability i.e., society, environment and economy, may give rise to ethical challenges;
- Creating or supporting citizens’ capabilities and opportunities for independent monitoring of the contamination and following up the remediation process and its outcomes, can contribute to citizen empowerment and enhancement of their confidence in decisions;
- As remediation objectives go way beyond reducing radiological doses, a purely technical risk-based process may lead to solutions that prove ineffective in the long-term, as it lacks sufficient attention to all of the scientific, economic, social and ethical dimensions;
- A decision framework that can accommodate, and balance, the objectives of more technical nature along with the social and ethical dimensions is required. That represents a challenge, for example, when reference levels are to be established and the overall remediation strategy is to be selected.

4. STAKEHOLDER IN ENVIRONMENTAL REMEDIATION DECISIONS

The importance of stakeholder involvement in decisions related to all aspects of the nuclear fuel cycle - from uranium mining to decommissioning of nuclear facilities and environmental remediation also including radioactive waste management; is widely recognised. The International Nuclear Safety Group recommended, for example, "that all stakeholders with an interest in nuclear decisions should have the opportunity for full and effective participation in the decision-making process" [38].

4.1 RATIONALE AND ADDED VALUE OF STAKEHOLDER INVOLVEMENT

The trend towards more intensive interactions with stakeholders recognizes that environmental decisions have social and political, as well as scientific aspects [39], therefore require deliberation.

For decisions concerning an environmental remediation or decommissioning project, involving and engaging individuals whose lives are impacted by the decisions taken is crucial for the success of the project. Their participation and contributions to the decision process are essential, as they have a vested interest in the end result.

In a very broad sense, a stakeholder is any "individual or group of individuals (institutional and non-institutional) with a tangible or intangible (yet to be shaped or discerned) interest" in the scope of environmental remediation issues [40]. They may be able to influence decisions, be affected by the formulation and resolution of a problem or challenge or represent an affected party. In this perspective, stakeholders are constructed in interaction with actors, issues, and contexts [40].

For instance, in the case of environmental remediation, the regulator, the operator, the workers, the implementers, the people living or working in the local community, the community social networks, community leaders, technical and social science experts, media, authorities, NGOs, health professionals, are just few examples of stakeholders.

Care has to be taken to correctly identify the appropriate stakeholders at the beginning of the planning process to maximize opportunities to develop trust and firm working relationships and the chances for project success. The Fukushima case study presented in this publication also brings evidence that the scope of environmental contamination by radioactive materials after a nuclear accident may be vast and may include lands with various uses such as residential areas, farmland, and forests, and, in those situations, it may be necessary to consider and implement different decontamination methods simultaneously. With such a wide range of stakeholders, including the national government, municipalities, decontamination companies, and residents, it is necessary to conduct a study with such a wide scope and examine the relationships between people and their mutual trust as this will eventually become an important factor that will greatly affect the implementation of the remediation project.

Lessons learned from past experiences highlight the particular importance of including the local community in stakeholder engagement processes, both for practical reasons since they have important knowledge and insights, but also from a more fundamental ethical right to take part in decisions that affect their lives [10, 25, 41]. Paying due attention to stakeholders' opinions, understanding their views and perspectives and supporting effective involvement from the outset of the decision process will contribute to better decision-making, ultimately leading to the most responsible and appropriate approach. If stakeholder involvement is only used as a tool to increase awareness or acceptance of predefined, often short-term solutions, then the process becomes less impactful and sustainable.

As shown also by case studies in appendix, involvement of stakeholders, including the public, can bring clear benefits to environmental management projects by:

- Ensuring that the remediation end-state satisfies the legal requirements;
- Addressing social, cultural and technical issues appropriately and effectively;

- Supporting authorities to make cost-effective, community-specific and environmentally sound decisions;
- Ensuring that the interests of the residents are considered, e.g., the subsequent re-use, to the extent possible, of remediated areas;
- Reaching solutions that are accepted by the public;
- Providing citizens with first-hand professional information;
- Providing opportunities for implementers to explain remediation decisions in a non-technical way that can be understood by all the affected citizens;
- Avoiding potential conflicts and costly litigations;
- Stimulating social learning and facilitating the sharing of lessons learned;
- Building relationships and trust among the various stakeholders and trust in the decision-making process.

Broader than that, it has been shown that participation, not only increases *"the legitimacy of decisions and reduce[s] the level of conflict"* [42] but also increases the quality of decisions in many ways [39, 42]. By integrating expert assessments with citizen views, ideas, information, and analyses, the environmental remediation project can stimulate creativity and social learning [21, 42]. These ideas are also reflected in the recommendations for developing co-expertise processes in post-accident management, based on lessons learned in the aftermath of the Chernobyl and Fukushima accidents [43].

It has to be highlighted that while there are strong benefits for the industry to involve stakeholders more in the decision-making process (e.g., greater transparency, increased levels of acceptance, improved decisions) it is important to be clear that the decision-maker does not shift the responsibility for consequences of the actual decision.

Some authors argue that participation is successful when the process, including rules and roles for participation, are co-created together with the participants [44]. The case study on the South Alligator project in the appendix shows for instance how the composition of the consultative committee created to discuss how the concerns and aspirations of the Traditional Owners could be addressed was decided together with this group of stakeholders.

Early involvement has been recommended by both researchers and practitioners [25] [40]. According to the Fukushima case study reported in this publication it is of extreme importance to define the purpose of remediation measures and the expected results together with the stakeholders, so that a shared understanding can be created. The reported residents' dissatisfaction and distrust on the decontamination policy are attributed partly to the fact that the decontamination process was not understood neither shared in appropriate ways among the stakeholders.

In practice, not all stakeholders may be able or wish to participate in an involvement process. However, a reflection is needed on their potential needs and concerns. For instance, in the WISMUT project, also discussed in this publication, future generations were taken into account by integrating the remediation concepts into plans for sustainable development of sites and potential reuse.

Several guidelines and recommendations for stakeholder involvement have been elaborated by researchers, practitioners, radiological protection policymakers and civil society organizations and are described elsewhere [15, 40, 45-50]. These conclude that there is no generic 'all size fits all' participation model that can be directly applied to any environmental remediation project by institutions willing to initiate stakeholder involvement processes [48, 49]. The cultural, social, economic, technical, environmental, historical, and political dimensions of the environmental remediation projects are site-specific and need to be taken into account when designing and conducting these processes. Objectives have to be clear and adapted to the context, the target stakeholders, and the expected influence on the actual decisions of those participating.

4.2. TAILORING STAKEHOLDER INVOLVEMENT TO THE CONTEXT

Participation covers a wide range of interactions such as release of information, two-way communication, collaboration and partnership and, citizens' initiatives (e.g., citizen science). Several typologies of public participation have been developed to describe this, for different contexts and following different lines of reflection. Some are centred around power and control, others on the motivation for participation, or the different interests at stake for the implementing agencies and for those invited to participate [51-54].

Various approaches can be used to enact participation, such as focus groups, citizen juries, workshops, advisory committees, citizens' networks, among others. A large body of social sciences literature investigated these approaches and their applicability, depending on the particular context of the decision problem, the objectives of stakeholder involvement, the foreseen influence on decisions, and the type of participants (e.g., experts and/or non-experts), documenting their advantages and potential pitfalls [55-57].

A mix of interactions and participatory approaches might prove most effective. For instance, the approach for 'Building Bridges with the Public' adopted by a remediation project in Germany (see Wismut case study in this document) included stakeholder involvement in the decision-making on remedial options and solutions for the safe disposal of radioactive materials and residues; unrestricted stakeholder access to all environmental data, including environmental impacts; active involvement of local firms and engineering consultants in the remediation project; annual environmental reports; "Miners' Day" and "Open House Days" events; preservation of mining heritage and traditions; exhibitions, scientific conferences and workshops. One major lesson learned in that project was that above all, great patience is required when dealing with remediation of complex legacy sites. The lack of information and records commonly associated with legacy sites does not usually permit rapid progress in project development and planning.

Enabling personal engagement of affected people with the issue, e.g., by involvement in problem formulation, data collection, choice of remedial solutions, development of solutions, helps create joint ownership of the remediation decision. A noteworthy example of action supporting personal engagement with the issue is the "information-market" concerning a remediation project in Belgium [58]. During this event, the opportunity was provided for community members to ask for personal advice from invited experts, which made the information discussed not only understandable but also actionable.

It is important to note that participation does not only take place at the initiative of governmental actors tasked with overseeing or implementing the environmental management efforts. Citizens also undertake actions to address environmental problems, in collaboration with, or independently from governmental institutions. One example is provided by the citizens' radiation monitoring centres in Japan after Fukushima. These networks helped fill information gaps and generate actionable and independent data in the immediate aftermath of the accident [34]. To this end, citizen networks continuously redefined their role with time, in order to respond to citizens' changing concerns and needs, for instance by creating records or providing mental healthcare services in addition to radiation monitoring.

Another example is the cooperation between farmers, distributors, and the food industry to restore public trust in locally produced food. This has been highlighted as one of the successful revitalization initiatives in the Fukushima Prefecture [59].

4.2.1. Importance of the legal context

The need for systematic approaches to stakeholder engagement in environmental remediation processes in national legislation, with definition of roles and responsibilities and proper allocation of resources, as well as clear rules of engagement have been highlighted as important facilitators for the involvement of stakeholders [25, 40].

In the USA, for instance, a National Environmental Policy Act stipulates, in a structured and transparent way, the role of the different actors and the opportunities for stakeholder involvement. It also includes a "Citizen's Guide" aimed at supporting the effective participation of citizens and organizations in the environmental reviews of Federal agencies [60].

4.2.2. Importance of social and cultural context

The social and cultural contexts are of particular importance when planning and conducting stakeholder involvement processes. Three levels where contextual factors play an important [61].

- Individual level: education, gender, social status, trust in actors organizing the participatory process, moral norms;
- Community level: extent of resource dependence, local belief systems, social networks, community awareness of the issue, community size and heterogeneity and;
- National level: rule of law, gender equality, accountability and transparency in the political system.

For instance, in the South Alligator case study, the use of an open-air venue with two days reserved for discussions, and an informal format whilst maintaining a structure, helped relieve stress and improved group dynamics in stakeholder meetings bringing together Aboriginal groups and representatives of governmental agencies. Even in the same country, different approaches might be needed. Another example is provided by Ref. [30] in a case study on the Shiprock disposal site for a former uranium and vanadium processing facility located in the Navajo Nation. This example highlights the importance of considering socio-economic factors and cultural differences when planning for public engagement and outreach. In that case, one-on-one and verbal communication proved a more effective means of communication with the Navajo Nation.

Communication with stakeholders is essential and need to be clear, honest and regular; it also has to be undertaken in a culturally appropriate manner Sometimes simplified language (not technical) and teaching approaches (e.g., explaining how to interpret groundwater contamination data, or showing how the contamination plume is moving) are needed. As revealed by the Fukushima case study, situations might occur when lack of explanation of the decontamination methods, constraints and expected results might lead to residents' dissatisfaction with the decontamination policies.

4.2.3. Importance of the contamination context

Lessons learned from several decades of experience in radioactive waste management, post-accident management and other areas show that a key issue is realizing and respecting how people define their communities, and what precisely may be affected by a project [15, 62, 63].

Perception of the situation, in general, and the environmental remediation in particular, may differ depending on the context. A case study concerning historical pollution at a NORM site in Belgium, resulting from a previous legal framework allowing those discharges to be made, illustrates this point [58]. As the remediation of the site was carried out by the industry responsible for the contamination, the process was positively perceived by the local population, as being the rectification of a past situation. This perception, as well as the limited health impact, was conducive to a smooth collaboration with the local population. Another specific element to the mentioned case study was the past and present employment of many people in the vicinity of the remediated site by the involved industry. As a result, people not only benefited from the presence of the industry, but also had more knowledge of the situation and therefore more expertise and trust.

The situation could, however, be different in another context. For instance, environmental remediation after a nuclear accident is associated with several scientific and societal uncertainties, asymmetrically perceived risks and benefits of the activity generating the radiological risk, societal distrust and stigma associated with affected areas [9, 10, 64, 65]. Furthermore, there may be challenges for stakeholder engagement associated with other decisions that have been taken. For instance, the Fukushima case study in this document highlights how obtaining consent in the special decontamination area was extremely difficult under the circumstances in which residents were scattered all over the country and had to live as evacuees.

The context of remediation can change in various ways, technical as well as economic or social (e.g., who the stakeholders are and what are their expectations). Technical designs have to meet regulatory requirements and the approval of stakeholders, but ideally, they would be flexible to accommodate any unforeseen changes that may develop during the working phase of the project. For legacy sites for instance, as the time period between remediation and contamination can span over several decades, the needs, concerns and opinions of stakeholders may be different at the time of the contamination, compared to the time of remediation. Certain issues that were high on stakeholders' agenda may have changed, priorities might have shifted, and awareness could have changed. For example, air pollution or effects of green spaces on health, may be on the agenda in the remediation phase, whereas this was less the case at the time of contamination. This shift in agenda setting influences stakeholders' perceptions of remediation efforts. Even the stakeholders may have changed; for instance, new residents might have come that are not very familiar with the contamination of the site and may different perceptions [26].

In practice, different communities might need to be involved in the decision-making process of a remediation project. That is a typical case when the waste generated with the remediation of a given site will be disposed or transferred to another area (away from the remediated site) in which a repository will need to be commissioned to accommodate the generated wastes with the said project. In such circumstances, the dialogue will need to include both communities in the pursuit of the final decision. Depending on the outcomes of this process, costs with remediation may escalate, also due to delays in the implementation of the needed works.

4.2.4. Impact of involvement processes on decision-making

An analysis of more than 200 documented cases of environmental decision-making (mostly related to in non-radiological contaminations) concluded that in most cases, public participation, especially more intensive forms of interaction with higher impact on decision-making, contributed to better decisions, by, among others, helping to create innovative solutions that better meet stakeholders' needs and concerns [39].

However, an exploratory review of stakeholder engagement in nuclear or radiological related environmental remediation projects undertaken in the development of this publication found that only a few documented examples of wider stakeholder engagement (including civil society actors) in decision-making are publicly available. Most of these reports are related to remediation projects in the United Kingdom or the United States of America.

It is suggested here that the lack of detailed information on wider stakeholder involvement in remediation decision-making processes might result from several interlinked reasons, such as:

- Lack of engagement/transparency projects developed during earlier times were predominantly implemented within the logic of 'decide-announce-defend';
- Narrow interpretation of who the relevant 'stakeholders' are;
- Some site operators might have engaged with stakeholders, but did not adopt a formal and documented decision-making process in which options and preferences were highlighted, scored and subsequently selected;
- Organizations may publish only an overview of remediation programs, without details related to supporting decision-making process.

Whenever a discussion about the decision-making process supporting environmental remediation related to a nuclear site is documented, it rarely goes into the detail on how stakeholders might have influenced the chosen option. Some examples can nevertheless be mentioned. Additional examples can be found in the case studies included in this report.

A notable example is the United Kingdom's Harwell site, where the operator at the time United Kingdom Atomic Energy Agency undertook the remediation of a series of legacy waste trenches known as the chemical and beryllium pits between the years 2000-2002. A formal Best Practicable Environmental Technology (BPEO) process was adopted to generate potential remediation options and ultimately select the most desirable option. A regulatory/local authority forum was utilized to provide participation in the scoring and assessment of options. Opinions on the preferred option were also probed by means of a public communication programme [66]. The outcome of the BPEO process led to the preferred option of complete removal of all wastes from the site.

At the United Kingdom's Sellafield site, the operator also undertook options assessment for the management and potential remediation of the existing legacy waste trenches. A flexible and qualitative assessment approach against a series of single or combined options was undertaken that might altogether represent the Best Available Technology (BAT). Following an initial analysis, three of the six options initially selected were taken forward to be submitted to more detailed assessment involving a range of attributes. This assessment was the basis for identifying a preferred option, namely the installation of a re-profiled and drained tarmac cap above those areas of the trenches that were not capped at that time. The solution was seen as providing an integrated single cap over the whole trench area. A key component of the options assessment process was a stakeholder workshop. Workshop participants represented a wide range of different stakeholder groups, including regulators (acting in an observer capacity). The main outcome of the workshop was to reach a consensus on the preferred interim management options for the trenches [67].

Another example is related to the Fernald site in Ohio, USA, a former nuclear production facility that ceased operations in the late 1980s. It provides a good example of collaborative decision-making where community involvement in the remediation process led to the successful remediation and reuse of the site. Community Groups were actively involved in helping to transform this legacy site into a community asset. They set out a series of ecological restoration goals to achieve a park with an emphasis on wildlife. Key objectives of the restoration included allowing some level of public access, the establishment of an education centre, and the reinternment of Native American remains. Opportunities for hiking, walking, environmental education and wildlife viewing were eventually achieved. Through holding around sixty stakeholder meetings a year, trust was built, and the reuse plan ultimately implemented gained support from stakeholders, regulators and the party responsible. This collaborative decision-making led to the adoption of a balanced clean-up approach, whereby eighty per cent of the contaminated soil and debris was retained on-site with the remainder requiring offsite disposal [68].

4.3. INVOLVEMENT OVER THE ENTIRE LIFE CYCLE OF THE PROJECT

Involvement of stakeholders in remediation projects is often focused on assessing options to determine, among other things, the remediation end state or the options for site reuse. But there needs to be greater consideration of the entire life cycle of the project so that a project can be reviewed more holistically. It is important that the remediation process is understood throughout its entire life cycle and does not focus only on short-term outcomes. For instance, an agreed level of remediation aimed at achieving relatively low dose rates might lead to significant volumes of waste. If there are no acceptable solutions for dealing with these wastes, then the chosen option might not be seen as the optimal one and might not be supported by stakeholders if the consequences had not been discussed.

An example was seen during the remediation work following the Fukushima accident in Japan. The government had initially set out to achieve an additional individual dose of 1 mSv per year as a long-term goal of the remediation activities in designated areas. However, this target was ultimately understood by the members of the affected communities as a short-term goal. In addition, the waste management strategy involved placing the wastes following remediation at Temporary Storage Sites (TSS) and then have the wastes moved to an Interim Storage Facility (ISF) where it would be sitting for thirty years before being moved to the final disposal site. The locations for the temporary storage sites were agreed with local stakeholders on the understanding that the wastes would be relocated in a pre-defined number of years. However, remediation works generated significant amounts of waste leading to the creation of additional temporary storage sites. The agreement on the construction of the ISF took longer than originally planned to be achieved. As a result, remediation wastes had to be stored in temporary sites for longer than originally anticipated and that culminated in erosion of trust from the stakeholders in the authorities. As the Fukushima case study in this document reveals, while a reference level between 1 and 20 mSv/year could be selected, it was found difficult to give a good justification to the residents of the affected areas that a figure above the lower end of the range could be chosen. As to make things even more complicated, the case study explains, according to the authors, a widespread perception that an effective dose of 1 mSv/year could be achieved solely by means of decontamination activities.

It has been noted the need for tools allowing citizens to ’access expert knowledge and to make informed judgements – including valuations – on complex policy issues’ [69].

In addition to new technological developments, new methods have been proposed for engaging with stakeholders, allowing visual or more immersive techniques of exploring the future of a remediated site.

Within MAESTRI, the use of social multi-criteria analysis will be explored as a decision-aid framework enabling more direct stakeholder involvement in the decision process (see section 4). The Malvezy case, in the appendix, illustrates how such a well-structured framework allowed its reuse with different weighting ratios for the evaluation criteria to illustrate other stakeholders’ points of view.

Multiple means of communication, e.g., including visuals, can also be helpful to facilitate involvement. In several case studies, such as the Rocky Flats project on radionuclide soil action levels in the US [70], or the French case study of the Malvezy site, discussed in this publication, the power of graphical methods to convey technical information to stakeholders, including citizens, is emphasized. In the latter case, ten criteria were used to support the decision process and were presented and fully documented through precise indicators. A significant effort of the technical project team was devoted to working on different visual presentations of the results. These visuals helped stakeholders to understand the significance of the results [71].

In recent years, advanced methods such as mixed reality have also been used due to their ability to connect “real and virtual worlds to produce new environments and visualizations, where physical and digital objects co-exist and interact in real-time" [72]. Using mixed realities can be one of the approaches useful in environmental remediation to help in engaging citizens and stakeholders in an immersive approach. For illustration, the United Nations (UN) urban planning unit UN-HABITAT [73] has deployed some of the techniques for mixed reality design to ensure inclusive urban space where a wide range of stakeholder groups are actively engaged and can have a say. Several guidelines to involve stakeholders using mixed reality in urban space have been developed; similar techniques could be used for environmental remediation [74]. Several necessary conditions were highlighted to maximize the chance of a positive outcome from the stakeholder involvement through mixed realities and technological approaches [75].

Other approaches include gamification. Deploying similar tools to reflect on the different aspects playing a role in remediation processes and involve a wide range of stakeholders in joint reflections is a promising path that needs to be explored. A relevant initiative in this regard has been developed in the European H2020 TERRITORIES (To Enhance Uncertainties Reduction and Stakeholders Involvement Towards Integrated and Graded Risk Management of Humans and Wildlife in Long-Lasting Radiological Exposure Situations) project [76]. In this project, an interactive dialogue tool initially developed “as an exercise in participatory and comparative evaluation of alternative long-term radioactive waste management paths” was adapted for the case of post-accident recovery. Different options of public policies were modelled, evolving between centralized and decentralized decision-making; and with decisions based only on radiological protection criteria or taking also social and economic aspects into consideration. The exercise discussed several necessary conditions to maximize the chance of a positive outcome from stakeholder involvement.

4.4 TAKE-AWAY FOR THE INVOLVEMENT OF STAKEHOLDERS

The main messages from this section are synthesized bellow and are addressed to regulators, operators and implementers of environmental remediation projects, and all actors initiating a stakeholder involvement process:

- Stakeholders have to be involved as early as possible, and throughout the whole process, starting from the definition of the need for environmental remediation and of its objectives and scope;
- Stakeholders need to be involved throughout the life cycle of the project, from environmental remediation to waste management and site repurposing;
- A consistent culture of honesty and transparency will be supported, with regular information;
- Environmental data Ough to be disclosed, e.g., through physical or digital reading rooms;
- The processes aiming at the involvement of stakeholders will be flexible, to i) consider both the legal requirements for stakeholder involvement, as well as the expectations concerning involvement of the different stakeholders, which can be broader than what is legally required; ii) consider that stakeholders, as well as their expectations, may change during the process;
- Stakeholders, including citizens and citizen groups, have to be provided with opportunities to express their views, and with explanations on how their suggestions or concerns have been addressed;
- Transparency is needed in all stages of the project, including the final decision-making.
- Stakeholder involvement have to be adapted to the cultural and other site-specific particularities: there is no “one size fits all” solution.
- The contribution of stakeholder involvement to increasing the quality of decisions on environmental remediation ought to be recognised;
- The process of involvement (its scope, objective, level of involvement, and rules of involvement) is most successful when it is co-produced together with stakeholders;
- The right of potentially affected people to be involved in decision-making has to be recognised;
- Including stakeholders in the decision-making process is not meant to be used to relinquish responsibility for the overall consequences of the remediation project;
- Stakeholder involvement processes and their specific role in decision-making deserve to be well documented, to ensure transparency and allow learning and cross-fertilization;
- National policies on decision-making for environmental management might need to include systematic approaches to stakeholder involvement;
- Participation is more efficient if an effort is made to provide information at the right level and in ways that ease the understanding of technical aspects by the participants;
- It is essential to understand and respect the ways in which people define their communities, and what precisely may be affected by a project.

5. FRAMEWORKS AND TOOLS FOR DECISION-MAKING

This section will review frameworks and tools that support decision-making in the scope of environmental remediation. The section starts covering Conceptual Site Models which is considered to be a starting point to implement efforts related to environmental remediation. After that, the section describes the main approaches that are used to support decisions related to environmental remediation and then focuses on the tools that can be used for that purpose. It is recognized that not all available tools might be reviewed in this section and also that Multi-Criteria Decision Analysis (MCDA) systems are widely behind many of these tools. Because of this reason, particular emphasis is given to MCDA.

5.1. CONCEPTUAL SITE MODEL

A starting point in any environmental remediation project is the establishment of what is called the Conceptual Site Model (CSM) which is a representation of the physical, chemical and biological processes that are in charge of the transport, migration and actual or potential impacts of the contamination in the different environmental media, i.e., soil, air, groundwater, surface water and sediments, to human and/or other receptors [77]. The development and refinement of the CSM will help identify potential data gaps as regards the site characterization and will support decision-making throughout the life cycle of a remediation project [77]. CSMs are used to assemble and integrate information such as past and current activities; the presence of hazardous materials or contamination; the physical, hydrologic, climatic and other environmental conditions; and potential transport and exposure pathways. To be most useful, a CSM needs to be developed at the start of a remediation project and be updated over time as the project progresses and new information becomes available. The level of complexity of the CSM, and the associated effort, will correspond to the complexity of the remediation issues, the stage of the project, and the decisions being made. Whenever CSMs are appropriately structured and maintained, they can be a valuable asset supporting the overall decision-making process that integrates project managers, technical teams and a wide range of stakeholders.

CSMs are also very effective in facilitating the involvement of different stakeholders and very useful tool for visualization of the many relevant features in public meetings. They support key analyses, such as risk assessment, remediation option selection, and key decisions, such as where to collect more data and what types of future uses for the site may be appropriate.

5.1.1. Types of data used in Conceptual Site Models

Any information or data related to a site have value, particularly if the quality control and quality assurance associated with the data is ascertained. Collection and use of data and information for nuclear sites and sites containing radioactive contamination generally fall into one of the following categories [77]:

- Historical Operations – this item includes, for the example, site infrastructure, operational history, disposal practices, spills, releases, and production capacity;
- Physical Features – under this topic information on the location of the site, its infrastructure, topography, weather patterns, surface water features, prevailing wind direction are collected;
- Geology – here one will be looking into regional geology, site-specific geological features, scale-appropriate measurements for the remediation life cycle;
- Hydrogeology and Hydrology – this is where information on surface water and groundwater elevations, aquifer geochemistry, piezometric surface, vertical and horizontal flow patterns is compiled;
- Radioactive contamination – this is a very important set of data as it will contain information on spatial distribution of the contamination, vertical distribution of the contamination, where appropriate information on the source of contamination (source term), details about contamination of aquifers including plume core and its dispersion and of course the type and activity

concentrations of the radionuclides of concern as well as other non-radioactive contaminants and relevant physical-chemical parameters;

- Receptors, potential reuse and redevelopment options – here one will focus on potentially impacted communities and ecological receptors, reuse scenarios will be addressed, and remediation/management strategies will be articulated in order to address specific redevelopment plans vis-à-vis the potential future uses of the site.

Site data and information may be collected during separate events and for differing purposes. What the CSM allows is the integration of these data sets into a single platform. With a CSM in hands, the project teams can, for example, understand the contamination plume morphology in the context of a spatially correct hydrogeological setting. Relatively speaking, geology at most sites does not change significantly over the remediation project life cycle. Hydro geochemistry of the water bodies however can vary significantly spatially and temporally.

5.1.2. Conceptual Site Model evolution over the life cycle of a project

Conceptual Site Models have different functions in different stages of a project's life cycle and that will impact the type of information that may be captured in the CSM. The uses of the CSM in different stages of a remediation project is further defined in [78] and are summarized below:

- Preliminary stage: at this stage, the CSM is used to compile and process all existing information to identify data gaps and uncertainties and determine subsequent data needs. It may include historical site data (geological or hydrological data, past sampling data, aerial photographs, operating records, product inventories) and documentation of interviews with site owners, workers, and stakeholders. It may include a preliminary diagram of potential transport and exposure pathways to support risk assessment. The Preliminary CSM may be suitable for sharing with stakeholders to gain inputs regarding the site;
- Baseline establishment at this stage, the CSM is refined per additional pieces of information, such as those that may be gained from different stakeholders. Information will then be used to identify data gaps, address quality objectives and indicators and point out to potential remedial challenges;
- Characterization stage here, the CSM provides the framework for capturing and synthesizing new site characterization data. It can be used to address questions regarding the nature and extent of contamination and to refine the understanding of the potential fate and transfer processes;
- Design stage: at this stage, the CSM is used to support the design of the remediation actions. In particular, the CSM will be used to identify additional missing data that might affect the performance of remedial action. The data set dealt with at this stage is considerably more robust than in previous stages of the CSM;
- Remediation implementation stage: at this stage, the CSM is used to guide remediation efforts, such as documenting activities, recording and assessing the impact of changing conditions, and optimizing remediation activities;
- Post-remediation and after care stage: at this stage, the CSM is used to maintain a record of the remediation project, document results of any long-term monitoring activities, and support analyses of site reuse options.

5.1.3. Conceptual Site Model in the reduction of a project's environmental footprint

With the Conceptual Site Model well defined, it is then possible to articulate the effects of different remedy solutions and therefore incorporate those options that minimize not only the environmental contamination but also the remediation actions footprints broadening the scope of the remediation objectives to a wider perspective of site management.

In this regard, a methodology was developed to provide a uniform approach to reduce the environmental footprint of remediation projects [79].

The methodology consists of a multi-step process that quantifies the onsite material use, waste generation as a result of the adopted interventions, water use, energy use, and air emissions of a given remedial action. Based on the analysis of all these factors, assessment of the ecosystem functionalities that could be affected by that remediation project is implemented. The results can be used to identify the major impacting factors, and to evaluate ways to minimize these impacts. It is important to note that reducing the footprint of a remediation project is fully aligned with the need that such environmental intervention is supposed to do 'more good than harm', i.e., minimizing the detriment of a remedial project will contribute to increasing its net benefit and by doing so making the justification of such project more visible to the wide range of involved parties.

According to [80], two types of impacts of remediation projects can be ascertained:

- Local impacts: would be those that are incurred on site, or close to the site, because of the remediation activities. For example, dust and odors affecting the local environment can be linked to remedial works such as earth moving. This is caused by the own nature of handling contaminated soils, where soil dust resuspension possibly with the volatilization of organic contaminants (whenever these species are present) can easily occur. Therefore, these impacts will normally be a key focus driver in social-environmental management planning;
- Widespread impacts: will involve those impacts related to water, waste, and energy. Impacts on water quality may be caused due to the discharge of contaminated water that was not properly treated or by discharges of run-off waters after leaching contaminants from soil or waste stockpiles. Wastewater resulting from decontamination of equipment and tools can also be a source of secondary contamination. In terms of waste, the production of such materials may arise from treatment processes, including waste oil, waste chemicals, removal of contaminated soils and sludges, discarded materials, and other wastes. Finally, one has to pay attention to energy conservation and CO_2 emissions reduction.

Following the above considerations, the traditional approach to assess a remediation project is based on the understanding of the effectiveness and appropriateness of the particular remediation method to meet the remedial goals. It focuses on considerations about the easiness of implementation, the remediation costs and finally the remediation timeframes. However, such an approach may not account for all potential environmental impacts of the remediation activities including energy use, waste generation, emissions, and transportation-related impacts, and it does not account for the net environmental benefits of the remediation action either in a wider scale.

Addressing all these issues through a holistic approach will ensure the protection of health and the environment while minimizing environmental impacts associated with these interventions [81]. By applying sustainability principles to remedial actions, opportunities to reduce the overall environmental footprint of the remedy will become clearer with possibilities of optimizing related costs [82, 83].

5.2. MAIN FRAMEWORKS USED TO SUPPORT DECISIONS

It has been demonstrated that the CSM is a pre-requisite to decision-making for environmental management of radioactively contaminated sites. The next step is to choose the approach, or framework to structure the decision-making process in a more holistic way. This step has implications on the entire process, the alternatives and criteria that will be considered, and how stakeholder preferences will be included in the process.

Decision frameworks include “principles, processes, and practices to proceed from information and desires to choices that inform actions and outcomes” [84, 85]. By offering "conceptual structures and principles," they play a facilitating and enhancing role in decision-making processes. These structures and principles are instrumental for the inclusion of economic, social, ecological, ethical, technical, legal or institutional aspects into decisions. [85].

These principles, processes and practices are framed within decision theory and the discourse of stakeholder participation and power-sharing. Framed within this discourse ‘top-down’, ‘bottom-up’ or ‘shared’ decision-making approaches are dominant.

Multi-Criteria Decision Analysis (MCDA), Cost-Benefit Analysis (CBA) and Life-Cycle Assessment (LCA) are frameworks frequently encountered in environmental decision-making and coded into decision-support tools. They all provide a structured approach to support decision-making (see Table 1), albeit they differ in their main focus.

MCDA consists of integrative methods, while the other two methods are sectorial methods developed for economic analysis (CBA) or environmental impact analysis (LCA). Although more recent applications of CBA and LCA try to include also other considerations, such as social impacts, they find best use within the sectors and disciplines (e.g., economy or ecology) they have been designed for. CBA and LCA can also be used in combination with MCDA, whereby input on economic costs or ecological impacts are assessed using CBA or LCA, respectively, while the social impact is assessed using other methods.

Common to approaches in the MCDA category is their aim to develop structured and inclusive processes to determine satisfactory solutions to a given environmental management problem, given a plurality of preferences and socio-technical dimensions that cannot be always brought to a common, e.g., monetary, scale.

CBA focuses on evaluating the net benefit for society as a whole, based on the monetary value of costs and benefits of the different decision alternatives, albeit more recent forms of CBA make allowance for the inclusion of some social and ethical considerations in other than monetary terms [35]. It can be said that CBA focuses on one objective – economic efficiency - and one institution – the market – only. Different objectives and values such as sustainability or fairness cannot be readily integrated [86]. In-depth comparison of social multi-criteria evaluation and cost-benefit analysis is provided in [87]. This study argues that the two methods compete if all impacts can be translated to monetary values and economic efficiency in case the latest is the guiding principle in the established policy.

Life Cycle Analysis is also increasingly used for environmental decision-making, to guide the search for a “socially relevant and well-documented decision”, taking into account all stages of the activities [88]. In the context of environmental remediation, LCA can be used to identify ways to improve environmental performance, implement corrective measures across the life cycle and to optimize remediation strategies. LCA allows to identify and evaluate all inputs, outputs and potential impacts of a product or project across its life cycle.

TABLE 1. STEPS INVOLVED IN MCDA, CBA AND LCA ANALYSIS [86-88]

Multi-criteria decision analysis	**Cost-Benefit Analysis**	**Life-Cycle Assessment**
Identification of relevant stakeholders for the problem at hand	Choice of costs and benefits to be taken into account.	Create an inventory of consumption and emission measurements of different substances (environmental interventions).
Identification of stakeholders' values, desires and preferences.	Transformation of costs and benefits into money figures.	Impacts Evaluation and Classification: identify impact categories affected by the system in study.
Creation of policy options and selection of evaluation criteria (in participatory forms of MCDA or multi-criteria evaluation this involves co-creation of options by analysts and stakeholders or social actors).	Selection of the social discount rate.	Characterization: contribution of the system to potential impacts (environmental threats), w.r.t. environmental interventions (or environmental damage).
Construction of the multi-criteria impact matrix	Selection of the time horizon considered relevant for the decision problem.	Normalization (Technical Relevancy Analysis): specific contribution from the system studied on a specific area and in a given moment.
(only in Social Multi-Criteria Evaluation) Construction of an equity impact matrix of each option for the various social actors.	Choice of a mathematical aggregation rule.	Valuation: system impacts are presented according to their relative importance and aggregated. In this phase, subjective values are included to compare options
Application of a mathematical aggregation procedure (this may involve group deliberation or individual assessments by different stakeholders and is accompanied by deliberation in deliberative forms of MCDA).	Sensitivity analysis of results	Interpretation, expressing the results in function of the study's goal (e.g., choose between several options).
Sensitivity and robustness analysis of results concerning impacts, model parameters (e.g., weights), and exclusion/inclusion of different criteria.	Sensitivity analysis on impacts and model parameters (e.g., discount rates).	Total uncertainty based on the uncertainty of all parameters and model choices.

LCA evaluates "environmental charges, material and energetic resource, and residual running outputs, which flow inside the system under study" [88] and translates potential impacts into physical impact indicators. Examples of indicators include, for instance, the contribution to the greenhouse effect or the resources depletion. Several open issues for LCA are highlighted in [88], among which the difficulty of establishing priorities between the different environmental impacts. This complexity increases when social criteria are also considered. In that regard, multi-criteria evaluation can be a useful enveloping framework for LCA [88]. Table 2 based summarizes main characteristics of MCDA, CBA and LCA.

Cost-Effectiveness Analysis is another economic method commonly used, which considers both economic costs, as well as the effectiveness of achieving a specific physical target (e.g., reduction of external dose) [87]. CEA can thus be seen as a particular case of a multi-criteria analysis problem, since it has to deal with at least two criteria (cost and achievement of the physical target).

TABLE 2. SOME CHARACTERISTICS OF MCDA, CBA AND LCA BASED ON [86-88]

	MCDA	**CBA**	**LCA**
Efficiency	Multi-dimensional	Economic	Ecological
Compatibility with simultaneous inclusion of social, environmental and economic goals	+	-	-
Values included in the analysis	The plurality of social values and perspectives	Consumer preferences	Physical impact on the environment
Structured approach	+	+	+
Stability of ranking when adding/removing an alternative	+ : multi-attribute value/utility methods -: outranking methods	+	+ (depending on the aggregation method used)
Transparency of policy consequences	+	+/- (Background data may increase transparency)	+
Transparency of impact aggregation	+/-	+	+
Local context embeddedness	+	+/-	+/- (if social aspects considered)
Social learning	+	-	-
Time needed	-	+	+/-
Sustainability (time dimension)	Through sustainability criteria included in the analysis	Discount rates: trade-off between present and future benefits for society as a whole	Considers potential impacts in all stages of an activity.

As a final note, some guidelines for sustainability assessments (see e.g., SuRF UK guidance in section 5) recommend a tiered approach, depending on the problem and the remediation options considered. LCA and CBA have a high degree of complexity that might not always be needed. In some cases, a simple qualitative (tier 1) or semi-quantitative (tier 2) MCDA type approaches may be sufficient to allow a comparative analysis of the remediation options. More detailed economic or environmental assessments (tier 3) might include CBA or LCA components.

5.2.1. General considerations for a holistic decision-making process

In general, it is argued that the inclusion of social, economic and environmental criteria will allow for a more balanced decision-making process for environmental remediation [90]. Consequently, a complex decision-making process involving multiple stakeholders and multiple dimensions could benefit from the support of multi-criteria decision analysis (MCDA), due to its ability to include in a structured, transparent and consistent way a plurality of preferences, socio-technical dimensions and equity issues [87, 89-91]. Different perspectives inevitably result in different views but organizing discussions around a structured framework can lead to better understanding and more consensuses on model inputs.

Social decisions involve multiple and incommensurable values, which cannot be reduced to one single metric (such as money or energy). This key point can be analyzed by using the philosophical relationship between the concepts of comparability and commensurability [21, 86, 92- 95]. In summary, it is possible to prove that different metrics are linked to different social objectives and values; in this context, the statement *'option **a** is better than option **b**'* requires an answer to two questions: 1) according to what? and 2) according to whom?

On the contrary, incommensurability allows to compare various options under a range of multidimensional impacts. This is the basic idea of multi-criteria decision analysis. For example, when aiming for sustainable decisions, neither an economic reductionism, nor an ecological one, is adequate. Economic sustainability will in general have an ecological cost, while ecological sustainability also involves an economic cost. An integrative framework such as MCDA is therefore needed.

The main driver is the fact that in a public policy framework, the use of various criteria has a direct translation in terms of a plurality of social values and preferences. From this point of view, MCDA can be considered as a tool for implementing 'political democracy'. The use of a multi-criteria framework is also a way for implementing a multi/inter-disciplinary approach. In terms of inter-disciplinarity, the main difficulty is to construct a set of criteria that all social actors agree with. As regards the multi-disciplinarity aspect, the main issue is to compute relevant and consistent criterion scores. In a MCDA framework, the efficiency and effectiveness of the interaction process can improve a lot.

In summary, MCDA can allow the implementation of inter/multi-disciplinary for the research team and public participation for the local community.

Historically, the beginning of MCDA is characterized by the multi-criteria decision-making (MCDM) paradigm. In this framework, policymakers have to express well-structured preferences and then decision scientists apply a mathematical algorithm finding an "optimal solution" [96].

However various scientists showed that a mathematical model is not the only factor to assess the overall decision process quality [96]. Multiple-Criteria *Decision Aid* proposes instead a theoretical framework aimed at helping decision-makers to learn about their own preferences so that it is possible to make a decision in line with their objectives [96].

One of the MCDA frameworks that brings together natural and social sciences and offers a structured approach to include stakeholders' input in all stages of the decision process is Social Multi-Criteria Evaluation (SMCE) [21, 97].

The SMCE framework consists of the following seven main steps [97]:

- Identification of the relevant social actors, e.g., based on an institutional analysis;
- Definition of social actors' values, desires and preferences by using e.g., focus groups, anonymous questionnaires and personal interviews;

- Generation of policy options and selection of evaluation criteria, as a collaboration between scientists and social actors. In this way, evaluation criteria become a technical translation of social actors' needs, preferences and desires. For example, if a local community has worries about the possible noise produced by windmills, a possible evaluation criterion is sound pressure computed in decibels; if there is a desire to keep younger generations in a rural area, a clear relevant criterion is the number of people employed by the wind park;
- Construction of the multi-criteria impact matrix synthesizing the scores of all criteria for all policy options;
- Construction of an equity impact matrix, which describes the impact of each policy option from the point of view of the various social actors. This step is a peculiarity of the SMCE approach.
- Application of a mathematical aggregation rule to rank the available options. The importance of mathematical algorithms is their ability to provide a consistent aggregation of heterogeneous criterion scores. The multi-criteria paradigm provides thus a definite answer to the objection that the aggregation of different dimensions is impossible;
- Sensitivity and robustness analysis aims at addressing aspects of abstraction from reality required of any modelling exercise, i.e., checking the relevance and the explicit capacity of the theoretical framework used to structure and understand a policy problem. To this end, at the sensitivity of results to the exclusion or inclusion of different criteria, or the variations in criterion weights or dimensions [98]. In practice, while this analysis appears technical, it will always involve a social component. For instance, the inclusion or exclusion of a given dimension, or set of criteria, is generally the result of a complex process involving social, political and scientific considerations, as well as the inclusion of exclusion of specific social values and social actors.

The seven steps described above are not intended to be seen as rigid. On the contrary, flexibility and adaptability to actual situations are among the main advantages of SMCE. As a tool for policy evaluation and conflict management, SMCE has demonstrated its applicability to problems in various geographical and cultural contexts [99, 102].

5.2.2. Key definition for multi-criteria decision analysis

The MCDA process builds on several key concepts, including dimensions, objectives, criteria, weights, criterion scores, impact matrix, and compromise solution [96, 104-106]. At the highest level of analysis, a dimension defines the scope of objectives, criteria, and criterion scores. Objectives represent the desired direction of change, such as minimizing costs, minimizing social impacts, or maximizing ecosystem health. Criteria (sometimes also called indicators) serve as technical tools for associating an option with a variable indicating its desirability and consistency with the chosen objective.

Weights are often used to reflect the relative importance of dimensions, objectives, and criteria. The most common practice is to use equal criterion weighting, but this approach can lead to significant differences in the weights of objectives and dimensions. Alternatively, different criterion weights can ensure that all dimensions are weighted equally. A reasonable practice is to start by giving the same weight to each dimension and then splitting the weight proportionally among the objectives and criteria of that dimension. However, it is important to remember that weights can only be used as a measure of importance if combined with non-compensatory aggregation mathematical rules.

Criterion scores are evaluations of the impact consistent with a given criterion about a policy option and can be either qualitative or quantitative [107]. An impact matrix presents information on various criterion scores in a structured way, with each element of the matrix representing the performance of each option according to each criterion. For example, let us take into consideration an imaginary environmental remediation problem with three dimensions (economic, social and environmental), six criteria and a set of four policy options. This problem is represented in the impact matrix shown in Table 3, that is a mixed one presenting crisp number (cost), fuzzy numbers (employment) and qualitative information (all the other criteria).

TABLE 3. IMPACT MATRIX OF AN IMAGINARY ENVIRONMENTAL REMEDIATION PROBLEM

Impact Matrix				
	Alternative A	Alternative B	Alternative C	Alternative D
Financial Cost (Millions euro)	130.2	130.5	150	220
Avoidance Social Exclusion	Approx. 500	Approx. 700	Approx. 800	Approx. 600
Employment (pers/year)	Very Good	Fairly Good	Good	Very Good
Recreational attractiveness	Fairly Good	Fairly Good	Very Good	Good
Residential Attractiveness	+	++	=	+++
Environmental Impact	Very Good	Neutral	Very Good	Very Good

At this stage, one may ask what are the challenges involved in solving multi-criteria problems, represented in an impact matrix. One of the biggest challenges in solving multi-criteria problems is the fact that there is no ideal or utopian solution that optimizes all criteria simultaneously. Therefore, it is necessary to find compromise solutions that balance the criteria. Another challenge is that traditional methods, such as the "plurality rule", meaning that the option which is most often ranked in the first place is the winner, may not be effective. In fact, they only consider the first position in each criterion ranking and ignore all other positions [108]. To solve multi-criteria problems, it is necessary to consider the entire ranking of options, as well as what the majority of criteria prefer and what they reject. The whole information contained in the impact matrix, that is the intensity of preference, the number of criteria in favour of an option, weight, and relationship of each option with all the other ones, has to be exploited.

The relationships between the multi-criterion problem and the social choice problem have been analyzed in [109], where it is shown that 'Arrow's impossibility theorem' proving that there is no perfect voting rule [110], applies to MCDA, too. Consequently, only 'reasonable' mathematical algorithms can be developed in this field. Reasonable here means that algorithms can be evaluated not only according to the *formal properties* they present but also overall, according to the empirical consequences implied by their use too (e.g., environmental management). One example being the issue of compensability that arises when evaluating options with both positive and negative impacts [97, 106, 112, 113]. This means that a good score in one criterion may compensate for a bad score in another. For example, in evaluating a policy option that presents a very bad environmental impact and a very good economic impact, it is clear that allowing or not for compensability and to which degree is one of the key assumptions.

The most widespread compensatory methodology is Multiple Attribute Value Theory (MAVT), *which* assumes a decision-maker who always *"*believes that in a specified decision context there is a particular preference structure that is appropriate for him/her" [96]. This preference structure expressed in the form of a mathematical function aggregates the different criteria (generally referred to as attributes) so that the decision problem is:

$$max\ V(\mathbf{g}\ (a_n)) \text{ such that } a_n \text{ belongs to } A \qquad (1)$$

where $\mathbf{g}\ (a_n)=[\ g_1(a_n),\ldots,\ g_M(a_n)]$ and $V(\mathbf{g}\ (a_n))$ is a value function aggregating the M criteria. The role of the analyst is to determine this function.

In the framework of MAVT, complete compensability is always assumed. As stated clearly by [96] '*our problem is one of the value trade-offs'*. A trade-off between two criteria measures the amount a decision-maker is ready to accept as an improvement in one criterion to compensate a loss of one unit in the other criterion. In practice, determining such trade-offs in precise terms is very difficult.

The simplest and most commonly used, MAVT preference structure is the *linear aggregation rule*, where obviously weights are always trade-offs. Unfortunately, many practitioners consider weights as importance coefficients in a linear aggregation rule; this practice is incorrect from a theoretical point of view and may lead to distorted results. Moreover, one has to consider that a linear aggregation rule is a good representation of a decision problem only if preference independence among criteria exists. This means that each criterion score can be aggregated independently on other criterion performance, thus synergy or conflict phenomena are always hidden.

In real-world policy problems, partial compensatory aggregation rules such as the "outranking methods" are often desirable [96]. These are Condorcet consistent methods, based on pairwise comparison of alternatives. In their framework, weights have the meaning of importance coefficients and thus there is no need to assess complex trade-offs. Moreover, it is worth noting that the presence of qualitative information is a common occurrence in evaluation problems concerning socio-economic and environmental issues, and consequently methods that can handle both qualitative and quantitative criterion scores are desirable [114, 115].

However, two methodological problems are connected with all the outranking methods. First, Arrow's axiom [110] of independence of irrelevant alternatives does not apply; thus, the phenomenon of rank reversal may appear. This means for instance that the preference between ***a*** and ***b*** can change in function of the fact that a third option ***c*** is considered or not[3]. Second, the Condorcet paradox[4] may appear, i.e., alternative ***a*** may be ranked better than ***b***, ***b*** better than ***c***, but nevertheless ***c*** is ranked better than ***a*** [116].

An aggregation rule that is simple, non-compensatory and minimizes the rank reversal phenomena is Kemeny's rule [117, 118]. Moreover, it was explicitly designed to solve the Condorcet paradox, thus cycles are never present. Its basic idea is that the maximum likelihood ranking of decision options is the ranking supported by the maximum number of criteria (or criterion weights) for each pair-wise comparison, summed over all pairs of options considered.

When comparing the four options according to the six criteria described in Table 3, under the assumption of equal criterion weighting, the following pairwise comparisons are obtained:

[3] Arrow's axiom of "the independence of irrelevant alternatives" states that the selection made in the set of alternatives *A* depends only on the ranking made in that set. Alternatives outside *A* (irrelevant since the decision refers to *A*) will not influence the selection inside *A*. Empirical experience does not often support this axiom.

[4] The Condorcet Paradox definition is based on a theory that draws attention to some flaws of the social choice theory. It was proposed and proved by French mathematician Marquis de Condorcet. The paradox focuses on the explanation that, in some cases where there exist more than three or more preferences, the results of the majority preference may not represent the individual preferences. The Condorcet Paradox denotes the state where majority preferences are cyclical but individual preferences, which construct majority preferences, are not.

TABLE 4. PAIRWISE COMPARISONS OF OPTIONS IN THE EXAMPLE PROBLEM

	A	B	C	D
A	0	0.6	0.6	0.3
B	0.4	0	0.3	0.3
C	0.4	0.7	0	0.6
D	0.7	0.7	0.4	0

Then, the corresponding scores of all possible rankings are the ones summarized in Table 5, indicating as top options both the alternatives C and D.

TABLE 5 SCORING OF ALL POSSIBLE RANKINGS OF OPTIONS FOR THE EXAMPLE PROBLEM

B	A	D	C	2.4
B	C	A	D	2.4
B	A	C	D	2.5
B	D	C	A	2.6
A	B	D	C	2.6
B	C	D	A	2.7
B	D	A	C	2.7
C	B	A	D	2.7
A	B	C	D	2.8
D	B	C	A	2.9
A	D	B	C	3
C	A	B	D	3
C	B	D	A	3.1
D	B	A	C	3.1
A	C	B	D	3.1
D	C	B	A	3.2
A	D	C	B	3.3
C	A	D	B	3.3
D	A	B	C	3.3
C	D	B	A	3.4
A	C	D	B	3.5
D	C	A	B	3.5
C	**D**	**A**	**B**	**3.6**
D	**A**	**C**	**B**	**3.6**

Ref. [108] argues in favour of using the Kemeny aggregation method for ranking options, stating that the "only drawback of this aggregation method is the difficulty in computing it when the number of candidates grows". A numerical algorithm for efficiently solving this computational drawback has been developed recently [119] and it has been implemented in a software tool called SOCRATES (SOcial multi-CRiteria AssessmenT of European policieS) [120].

In conclusion, solving a multi-criteria problem involves dealing with the issue of compensability and finding a compromise solution that satisfies as many criteria as possible. Various methods and approaches have been developed to tackle multi-criteria problems, including MAVT and outranking methods. The choice of a method depends on the nature of the problem at hand, the information used in assessing the criterion scores and the preferences of the decision-maker.

5.2.3. Multi-criteria decision analysis in the scope of remediation activities

In practice, the use of the MCDA framework for environmental remediation can be seen to encompass multiple tools and decision-making methods that, in various ways and to various degrees, seek to include social, environmental and economic considerations in the decision process, with a trend towards sustainability, and allow for the sharing of decision-making power with various stakeholders.

Various scholars and practitioners highlighted opportunities and challenges of using the MCDA to support decision making for environmental remediation. These are related to the level of stakeholder participation, legitimacy, uncertainty, in (ter) dependency of criteria, stakeholder perceptions, the inclusion of societal costs, and dealing with complex sites. Below, a brief discussion is offered on each one of these elements.

5.2.3.1 Level of stakeholder participation

Stakeholders are often recognized in MCDA case studies as an important source of information for social criteria and, to a limited extent, for economic criteria. However, their participation can be much more than just gathering or provision of information. Stakeholders can be involved in all stages of the process, for instance by helping to establish the remediation goals, the management options, the evaluation criteria, and by expressing their preferences through the weighting procedure of evaluation criteria. It is proposed that that if stakeholders are involved consistently during the decision-making stage, the credibility, defensibility and acceptability of the remediation schemes, as perceived by the affected communities, can be enhanced [121, 122] indicated. It has been argued that the MCDA framework is helpful for guiding interactions with stakeholders in all steps of the decision process. MCDA was used, for instance, in a sediment management project in Norway to help stakeholders with the interpretation of the relevant information in a more structured way [123].

These examples illustrate how stakeholders can be involved in MCDA studies for environmental remediation. Systematic approaches for stakeholder involvement in MCDA will also be explored within MAESTRI.

5.2.3.2. Stakeholder legitimacy

The involvement of a broad range of stakeholders has been advocated [91]. However, it was recognized that the number of participants in an MCDA will ultimately be constrained by the weighting method chosen for the evaluation criteria and the level of participation envisaged. It recommended that the weighting methods have to allow for a plurality of values to be included, thereby lending decisions in remediation greater legitimacy. A thorough institutional analysis is suggested as a good way to identify relevant social actors [21].

5.2.3.3 Accounting for uncertainty

Several sources of uncertainty may influence the MCDA results [124]. They may be external (e.g., related to impacts of the different remediation options); or internal (e.g., related to specific model parameters). Uncertainties may also be related to the type of model chosen to represent preferences, or to particular way in which stakeholders, criteria and decision alternatives have been identified.

Uncertainties have, for instance, been modelled through the use of multi-criteria utility functions, in relation to decision-making for the remediation of contaminated soils [125]. It was concluded that the geo-statistical uncertainties of the log-normal distributed soil contamination has to be taken into account. If uncertainties are not considered, the final decision may be significantly distorted leading a decision-maker to have a biased deliberation between remediation alternatives at each possible state of contamination and as a consequence increasing the likelihood of making unwanted decisions.

It has also been demonstrated that the impact of uncertainty of the stakeholder preferences can be significant even driving the management decisions [90].

Stochastic multi-criteria acceptability analysis (SMAA) has been used to integrate the uncertainty and ambiguity elements to assess the robustness of sediment management alternative prioritization [127]. Monte-Carlo simulations were used to explore all feasible values for impacts and preference weights.

In another study, a 'Risk-based land management (RBLM)' approach was used, integrating risk assessment practices with more traditional site-specific investigations and remediation activities [128]. While it is argued that RBLM is a practical, scientifically defensible, and cost-efficient method, it is constrained by the accuracy of risk assessment models used and uncertainties.

In general, it can be observed however from case studies in the literature that applications do not always consider uncertainties. This is an attention point within the MAESTRI project.

5.2.3.4. In(ter)dependence of criteria

It has been argued that in complex problems, such as contaminated site remediation projects, the independence of involved criteria is not a realistic assumption [129]. A methodology was thus proposed in Ref. [129] that models that inter-relations between the economic, environmental, social, and technological considerations in order to indicate the most sustainable practice.

Another approach encountered in case studies entails the Analytic Network Process (ANP), which can handle more complex decision structures with interdependence between criteria and feedback mechanisms [130]. With the ANP methodology, it becomes possible to consider inter-criteria influence and feedback mechanisms to evaluate remediation alternatives. This could provide a more realistic and structured way to understand the complexity of the decision problem.

5.2.3.5. Stakeholder perceptions

MCDA offers a way to account for stakeholders' perceptions of remediation technologies in the decision-making process; these perceptions may be different that those of experts. It has been found [131] that stakeholders participating in their study were more worried about the application of chemical remediation technologies, compared to those involving physical and thermal processes. In turn, the latter caused more concern than the biotechnology-based approaches. It has thus been concluded that such concerns can be reduced through direct involvement of residents.

Upon examination of residents' acceptance of different remediation technologies among residents in New South Wales – Australia, similar conclusions were confirmed about the use of different technologies [132]. In this case, it was found that residents preferred the options of Monitored Natural Attenuation and Bioremediation when compared to other remediation technologies. It was also found that residents would have been willing to pay an increase in yearly taxes for implementing such technologies instead of remediation technologies involving chemical processes. Along the same lines, people's preference for what can be called 'gentle technologies' such as phytoremediation and in-situ immobilization have been documented [133]. Therefore, it was proposed that that decision support mechanism will need to incorporate more strongly the so-called gentle remediation options into existing decision-supporting tools or decision frameworks to promote more widespread use and uptake.

5.2.3.6 Inclusion of societal costs

One of the most challenging aspects of decision-making is estimating the societal impact of remediation options and including these in the decision-making process in a systematic way. Placing a value on health and environmental impacts can be useful in supporting decisions on remedial interventions but may be quite difficult to be understood and accepted. In this regard, a risk-based economic decision analysis was proposed to assess three alternatives for remediating a site in Denmark [134] propose. The used methodology combines remedial costs, external costs to the environment and health costs associated with residual contamination left after remediation. It was found that the health costs were minor compared to the direct remediation costs and the environmental costs.

MAESTRI will investigate in detail social impacts of environmental remediation and the type of indicators that can be used to evaluate these impacts.

5.2.3.7 Complex sites

Complex sites require intensive environmental remediation and are usually associated with long periods of time so that remediation objectives can be achieved. Complex sites characteristics include, but are not restricted to:

- Complex geological conditions;
- Hydrogeological conditions;
- Geochemical conditions;
- Contaminant-related conditions;
- Large scale of contamination;
- Non-technical challenges.

The Interstate Technology & Regulatory Council (ITRC) in the USA made efforts to put together different players such as regulators, federal agency representatives, industry experts, community stakeholders, and academia, to compile resources and create new guidance on the remediation and management of complex sites [135]. The ITRC team recommended that an adequate approach would consist of adaptive site management to deal with these sites [135]. Adaptive site management can be seen as a flexible, comprehensive way to iteratively assess and make necessary adjustments to the adopted remediation strategy. Key elements of adaptive site management include tools for updating the conceptual site model (CSM), establishing milestones, defining a performance system to assess the performance of options and progress towards the set objectives, as well as decision criteria guiding potential revisions of the remediation strategy.

It is important to notice that for some complex sites it can be virtually impossible to clean up every unit at the same time because of limits in funding, personnel, and technology. Therefore, a proper understanding is needed of the consequences of delaying the remediation of a unit (a part of a site, an area of a whole site containing a dedicated installation) on different receptors (e.g., people, ecological, and eco-cultural resources). A list of attributes was developed that managers might wish to consider for successful remediation and the potential consequences of delaying remediation were examined [136]. The factors influencing decisions on whether the remediation of a unit may need to be delayed include, for instance human resources, information available, financial means, equipment, structural integrity, contaminant source, and resource vulnerability.

In such complex situations, any given remediation task may depend not only on other remediation projects but may also depend on other elements such as availability of transport, containers, interim storage and ultimate disposal routes. Availability of trained personnel needs also to be considered. If remediation is to be delayed one needs to account for consequences this decision may have for people (e.g., workers, site neighbours), plants, animals, ecosystems, and eco-cultural resources). Therefore, in assessing the pros and cons of this decision, the associated risks, benefits, and uncertainties for evaluating the consequences of delaying remediation need to be carefully weighted. Delaying remediation can have substantial effects on human health and safety in part due to the deterioration of structures (a negative effect) but can benefit from the decay of radionuclides (obviously those of relatively short half-lives) and advances in remediation technology.

5.3 MULTI CRITERIA DECISION ANALYSIS TOOLS

Many tools that use the MCDA methodology have been developed to support decision-making in environmental management. In the following paragraphs, an overview is provided of various tools and their opportunities for application. The examples showcase the current attention to sustainability. Indeed, some of these tools utilize sustainability as an overarching framework for the evaluation of remediation options.

This overview is not exhaustive, but exemplary for the current paradigms in decision-making in environmental and remediation. Moreover, it is not restricted to the remediation of radioactively contaminated sites. It is clear that relevant lessons from the remediation/management of sites affected by non-radioactive species can also be relevant to the same actions in the scope of radioactively contaminated sites.

5.3.1. Risk reduction, Environmental Merit and Costs

Historically, environmental projects have focused on restoring the soil to pristine conditions or reducing contaminant levels below given criteria. While this focus has its own merits, for many sites the said reductions may be difficult to be achieved or will result in very high costs. As a response to these considerations, the REC decision support system was developed [136]. The REC methodology helps to find the clean-up alternative that balances the clean-up efficiency, with the environmental impact at reasonable costs. The output of the tool consists of the evaluation of three indices: the environmental merit index, risk reduction index, and the cost index of the remediation alternatives. With these outputs, the decision-makers can make an informed decision on the strategy that suits the specific context and goals of the project.

5.3.2. Sustainable Choice Of Remediation

SCORE (Sustainable Choice Of REmediation) is an MCDA tool [138] developed to provide a transparent assessment of the sustainability of different remediation options to be applied to contaminated sites. Key criteria considered include economic, environmental and social sustainability considerations. Economic sustainability is included as the net present value. Social and environmental sustainability are assessed as the weighted sum of a number of social or environmental criteria. These were determined based on literature review, interviews, and focus-group meetings. To identify non-sustainable alternatives, SCORE, combines a linear additive model to rank the alternatives with a non-compensatory approach. It allows for the integration of both quantitative and qualitative estimations of evaluation criteria. It also provides a full uncertainty analysis of the results, utilizing Monte Carlo simulation. Furthermore, it is compatible with the integration of preferences and opinions of various stakeholders.

5.3.3. Influence based decision guide

The INSIDE tool [129] addresses the observation that modelling criteria interaction in decision-making problems is complex and often neglected. The authors suggest that their methodology supports the choice of a sustainable option for the management of contaminated sites. As a specific feature, INSIDE considers the interactions among the involved criteria, providing the best remediation strategy for the project, as well as a management plan for further improvements of the system. The methodology works with the economic, environmental, social, and technological dimensions to elicit ‘the most sustainable practice’. The authors recognize that the methodology still needs to be tested broadly with a wider variety of remediation problems.

5.3.4. Decision support system for the requalification of contaminated sites

The importance of spatial prioritization, when large areas are contaminated (mega-sites), was recognized [139]. It was argued that choice of remediation measures would need to be spatially prioritized based on human health risk, and the technological and budget constraints. To address this, they developed a methodology including hazard assessment, exposure assessment, risk characterization, uncertainty assessment and allocation of risk reduction measures. It uses Monte Carlo analysis to model the propagation of uncertainties from the input values into the risk estimate. The methodology is implemented in the Geographical Information System called DESYRE. DESYRE is a GIS-based software composed of six interconnected modules: Characterization, Socio-Economic Assessment, risk assessment, technological assessment, residual risk assessment and the decision module.

5.3.5. Spatial decision support system for regional risk assessment of degraded land

Starting from the observation that accounting for spatial variability is an essential step for sound exposure and risk assessments, a GIS-based decision support system SYRIADE was developed in [139]. The underlying methodology aimed at supporting the inventory of contaminated sites. The tool provides a risk-based ranking of potentially contaminated sites at a regional scale. A spatially explicit exposure diagram identifies the receptors, stressors and their relationship. The physico-geochemical processes linking the source with the affected environmental compartments include leaching, volatilization, aerial transport, sub-surface migration, and runoff to superficial water. The developed GIS tool is easy to adapt to the regional context of the project, allowing the practitioner to introduce the regional relevant parameters.

5.3.6. Evaluation of a technically and economically optimal remediation strategy

To address the problems found in complex sites with high uncertainties, the METEORS (Model for the Evaluation of a Technically and Economically Optimal Remediation Strategy) was developed [140]. The model allows for the evaluation of remedial actions based on the reduction in uncertainty regarding the site situation and the impacts of decisions on the future set of available remedial actions at later stages in the remediation scheme. This methodology allows for progressive insights in time with more data acquisition. The author concluded that a proactive attitude to remediation can be less expensive and even valuable if there are positive benefits associated with the end state of the site.

5.3.7. Remediation strategies after the Chernobyl accident

In 2003 the IAEA put in place initiatives that led to an internationally agreed methodology as well as a software tool called “ReSCA - Remediation Strategies after the Chernobyl Accident” designed to optimize rehabilitation strategies for areas affected by the accident [142]. The software draws on the experience gained in the aftermath of the Chernobyl accident. The process of optimization in ReSCA is governed by two criteria: the cost efficiency of remedial actions and the public attitude toward this action. The application of this tool produced diagnostics in some of the most affected countries by the accident. It suggested, for instance, that, in the occasion of the study, removal of contaminated soil from populated areas was a high cost-effectiveness measure (in terms of total dose reduction) in the case of Belarus. The authors recognize however that disposal of the contaminated soil, as was the case in Japan, could have raised problems. In the case of the Russian Federation agricultural remedial actions were deemed to be kept as a central element of remediation strategies. In a context such as that of Ukraine, it was proposed that only agricultural remedial actions such as radical improvement of fodder lands or application of ferrocyn to cows would be advisable.

5.3.8. United Kingdom sustainability assessment tool

In response to various challenges and critiques and in an attempt to include the notion of power-sharing in the multi-criteria analysis frameworks, an increased interest has emerged towards more holistic and sustainable decision frameworks. Aligned with this, multiple programmes supporting this mission have been developed. The Sustainable Remediation Forum in the United Kingdom [143, 144] provides one of the most widely applied sustainability assessment tools in the field of environmental remediation (see details in section Sustainability.

Recently, a Tier 1 qualitative sustainability assessment tool has been developed[5] by the SuRF-UK Steering Group and is available free of charge. This assessment can be used to compare different potential remediation options for three main sustainability aspects: i) environmental (including emissions to air; soil and ground conditions; groundwater and surface water; ecology; and natural resources and waste) , ii) social (including human health and safety, ethics and equity, neighbourhoods and locality, communities and community involvement, uncertainty and evidence), and iii) economic (including direct, indirect and induced economic costs and benefits, employment and employment capital, project lifespan and flexibility). At tier 1, the options are compared using ranks or qualitative qualifiers such as 'best', 'better', 'worst'. The SuRF-UK framework is also adaptable to more complicated tiers of semi-quantitative or quantitative assessment referred to as tier 2 or 3 assessments.

5.3.9. The Karlsruhe Institute of Technology multi criteria decision analysis tool

The MCDA-KIT tool was developed at the Karlsruhe Institute of Technology (KIT) within the context of the European-funded JRodos system (Real-time Online DecisiOn Support for nuclear emergencies [144]. The MCDA-KIT is generically applicable and equally supports both the scientific possibilities for evaluation of methods as well as the needs of end-users in an operative application. The MCDA-KIT integrates several well-known methods to normalize the criteria values (e.g., proportional, min-max, softmax), preference elicitation (e.g., AHP [145], swing weighting, direct weighting), and for the overall aggregation of impacts (e.g., weighted sum, weighted product, ranking, TOPSIS [146]). All these methods are supported by a user-friendly interface. Additionally, many modules for end-user communication are available, starting with simple visualization of results in various charts, analysis of stability and correlation, up to reporting tools providing HTML web pages and Microsoft Word documents, presenting the summary from the numerical results as human-readable text.

5.3.10. Public waste agency of Flanders multi criteria decision analysis tool

Public Waste Agency of Flanders (OVAM), the Flemish agency responsible for non-radiological waste and soil remediation, which is also responsible for NORM contaminated sites remediation has developed a multi-criteria analysis tool for selecting remediation options using the BATNEEC principle (Best Available Techniques Not Entailing Excessive Costs) [148]. Based on the site characteristics, legislation, best available techniques and expert judgement, soil experts pre-select three relevant remediation strategies which are afterwards evaluated in detail to three types of impacts, related to local and regional environmental aspects, technical and societal aspects, and financial aspects. The methodology prescribes the weights to be assigned to these categories: 0.45 for environmental aspects (0.33 local environmental aspects and 0.12 regional aspects), 0.22 for technical and social aspects and 0.33 for financial aspects. Indicators used include the level of achievement of statutory objectives, e.g. concerning soils and groundwater pollution, total waste load reduction, emissions to other environmental compartments, remediation period and policy objectives (local environmental aspects), use of raw materials and recycled materials, the production of non-reusable waste during remediation (regional/global environmental aspects), possible nuisance to the environment during remediation, restrictions on use after remediation, causing damage due to remediation, safety precautions (technical and social aspects), and costs of remediation, and value of residual contamination (financial aspects). Before using MCDA, the evaluation of remediation options relied on expert judgment; this also implied a weighting process, but without quantifying the preferences. The positive and negative aspects were indicated (with "+" and "-") and then the positive and negative aspects were counted. The switch to the use of MCDA for soil remediation was gradual and seen as "extremely suitable and by far the best way

[5] https://www.claire.co.uk/home/news/1476-surf-uk-tier-1-assessment-tool

to identify and include the different factors (e.g., financial, technical, radiological, acceptability) into decision-making" [58]. The set of criteria also changed over the years, reflecting the 'spirit of the time' in the decision-making process. Currently, environmental impact is an important factor, but that was not the situation in the past. Due to increased attention to green and sustainable remediation, a CO_2 calculator was also included in 2017 in the multi-criteria analysis tool.

5.3.11. United States Air Force sustainable remediation tool

Another initiative in the direction of addressing quantitative indicators for sustainable remediation is the US Air Force Sustainable Remediation Tool [149]. It is conceived to serve the following general purposes:

- Planning for the future implementation of remediation technologies;
- Comparing remediation approaches based on sustainability metrics;
- Providing a means to evaluate the optimization of the adopted remediation technology systems already in place. [149]

5.3.12. Social multi-criteria assessment of European policies tool

An MCDA software tool based on Kemeny's ranking method has been developed recently [119] and it has been implemented in a web application called SOCRATES [120]. SOCRATES interfaces are designed according to the principle of User Experience Design (UXD); thus, an intuitive and easy human-machine interaction is assured. The main objective of SOCRATES is to help the operationalization of the methodological principles of social multi-criteria evaluation (SMCE), which has been explicitly developed for public policy. All methodological and mathematical details behind SOCRATES can be found in [21] [118, 119].

SOCRATES is composed of three main modules: multi-criteria, equity and sensitivity analyses. SOCRATES allows the use of both quantitative (including also stochastic and/or fuzzy uncertainty) and qualitative (ordinal and/or linguistic) criteria. It provides a ranking of policy options according to the set of evaluation criteria (i.e., the technical compromise solution/s) computed by using the Kemeny non-compensatory aggregation rule.

A distinctive feature is the equity analysis, which accounts for the preferences of different social actors concerning the various alternatives. This allows the distinction between opinions (subjective evaluations) contained in the social impact matrix and the evidence contained in the multi-criteria evaluation matrix. The equity analysis provides:

- indications of the distance of the positions of the various social groups (i.e., possibilities of convergence of interests or coalition formations);
- the ranking of the alternatives according to actors' impacts or preferences (social compromise solution).

Sensitivity analysis is used to determine the stability of the rankings and the influence of input parameters. SOCRATES conducts both local and global sensitivity analysis.

Local sensitivity analysis determines the sensitivity of results with respect to the exclusion/inclusion of different criteria and dimensions; and the changes in the weights of dimensions, criteria or social actors. In this analysis, parameters are changed one at a time. *Global sensitivity analysis* examines instead all the possible combinations of criterion weights; in this analysis parameters are changed simultaneously. The information produced is synthesized into graphics, like the following one (see Table 6) showing the global sensitivity analysis of the MCDA problem showed in Table 3. Table 6 shows how many times each option is present in any rank position, and the percentage each rank position is occupied by each single option. In the example considered here, it is clear that alternatives C and D are clearly the best ones, whatever set of weights is used, consequently results are very robust.

TABLE 6. EXAMPLE OF GLOBAL SENSITIVITY ANALYSIS RESULTS

	1st Place	2nd Place	3rd Place	4th Place
Alternative A	187	588	586	139
Alternative B	9	104	167	1220
Alternative C	667	168	576	89
Alternative D	637	640	171	52

As illustrated above, there exist a wide range of tools. Some are qualitative, others are quantitative. Some are focused on technical assessments of risk, while others attempt to include social and ethical considerations. Again, some tools are effectively used for environmental remediation policymaking, while others remain at the level of expert exercises. Several tools provide opportunities for stakeholder involvement, but most are lacking in this respect. Furthermore, the tools differ in terms of customization possibilities, access to software and purpose.

The MAESTRI project will aim to bridge these gaps by bringing together state-of-the-art frameworks and tools developed in the nuclear and non-nuclear domains, with a view towards developing an interdisciplinary approach to support decision making in ER/EM situations and with the results of the study cases in hand point out to improvements to be achieved. For this purpose, the Social Multi-Criteria Evaluation approach on which MAESTRI is grounded, will also contribute to a better assessment of the social impact criteria to facilitate their inclusion in decision-making processes. Some first ideas are illustrated in section 5.

5.4 TAKE-AWAYS FOR DECISION SUPPORT FRAMEWORKS AND TOOLS

The main messages to be highlighted are depicted below.

- The Conceptual Site Model is a necessary step in the overall process of remediation implementation to understand the interactions of the different compartments; it can also serve to inform stakeholders about these interactions;
- When a public policy needs to be implemented, there is a need of comparing different options and evaluating them to assess, among others, their environmental, economic and social attractiveness;
- Multi-criteria decision analysis is an integrative and structured framework, allowing to balance and include the different dimensions into decision-making;
- The use of MCDA is decision support, rather than decision-making;
- MCDA enhances the transparency of decision-making, since all criteria are presented in their original form without any transformations into a common measurement scale (e.g., money, energy) and the preferences are directly included;
- Several, qualitative and quantitative multi-criteria decision analysis tools are available. Each MCDA method has strengths and weaknesses; the choice of the method has therefore to fit the context of the project;
- Policy options are often characterized by conflicts between competing values, perspectives, interests of different groups and communities. The first requirement for public policies to be considered fair is thus the respect of value pluralism; thus, the application of MCDA will not be only a technical exercise;
- The use of MCDA has to include the values and preferences of the relevant stakeholders in all phases of the decision-making process: from the formulation of the problem, through to the

definition of options and criteria, the evaluation of the importance of the different impacts and the formulation of the final decision; Social Multi-Criteria Evaluation enables the direct inclusion of a plurality of values and dimensions through the use of evaluation criteria;

— SMCE enables inter/multi-disciplinary approach to the decision problem and the participation of the local community in the decision process.

6. SUSTAINABILITY AS INTEGRAL PART OF ENVIRONMENTAL MANAGEMENT

Sustainable remediation can be taken as the practice of remediating contaminated sites in a way that environmental, economic, and social factors are balanced. The goal is to ensure that the benefits of remediation outweigh its impacts, and that the chosen solution is optimal through a balanced decision-making process. In other words it intends to maximize the net environmental, social, and economic benefits in the scope of contaminated site remediation. In recent years, the inclusion of sustainability considerations in environmental management and remediation has gained increasing importance [2, 150, 151]. It is now widely recognized by industry, governments, and academia that decision-making regarding environmental aspects cannot be fully and properly conducted if sustainability principles are not considered in the overall process.

The movement towards sustainable remediation practices in the nuclear field follows the global efforts to ensure that remediation works are affordable, feasible, effective and ultimately, sustainable. These goals will only be achieved through a large and multidisciplinary knowledge base that encompasses the natural, physical, engineering and social sciences, where the practical, economic, regulatory, environmental and social (local and wider) context is taken into account. Therefore, the sustainable remediation concept is key.

In this section, sustainability in the scope of environmental remediation will be discussed in more detail, together with a number of frameworks for sustainability assessment.

6.1. INTRODUCTION

Several initiatives and actions have been established to conceptualize and apply the principles of sustainability to both the processes and the options for remediation of contaminated land management. This reflects an evolution from technical solutions towards ‘green’ and ‘sustainable remediation’. This imperative has been also recognized in the nuclear field, particularly concerning legacy sites and the decommissioning of nuclear installations [2, 151]. This illustrates a potential shift from sustainability as a criterion to sustainability as an overall framework for environmental decision-making.

Sustainable Environmental Remediation (SER) is considered an important concept for soil and ground remediation and has as the ultimate goal to “ promote environmental well-being and human health and safety, to minimize negative impact during and post-application of certain remediation system as well as by a judicious use of limited resources” [152]. It is important to note that Sustainable Remediation is not a synonymous concept of Green Remediation, which is defined as “the practice of considering all environmental effects of remedy implementation and incorporating options to maximize the net environmental benefit of clean-up action” [153]. A comprehensive sustainability assessment provides the opportunity to consider all relevant factors, including social aspects, alongside the economic and environmental ones, in a structured way.

It has been pointed out in 2013 that there is a lack of methodologies for the evaluation of the socio-economic aspects of environmental remediation, and that few site characterizations processes include comprehensive sustainability assessments [154]. It was also noted that as remedial activities tend to focus on site-specific risks that do not account for external social and economic impacts, and that social costs are often not included in a site remediation impact assessment.

In the last decade, the development and use of social and economic evaluation indicators for a comprehensive sustainability assessment of remedial actions have been increasingly addressed by researchers and practitioners. The Sustainable Remediation Forum in the United Kingdom [143] is one of the programmes trying to incorporate a more sustainable approach to environmental remediation. Other frameworks and indicators considering positive and negative environmental, economic, and social effects can be found in the USEPA (United States Environmental Protection Agency) Green Remediation programme [79], the Network for Industrially Contaminated Land in Europe (NICOLE)

[155] or the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) five-year superfund review [156]. Implementations of these frameworks into environmental remediation projects can be found in [126, 138, 157-159]. The sustainable and resilient framework developed by the U.S. ITRC (Interstate Technology Regulatory Council) puts special attention to resilience against the increasing threats caused by climate change, such as extreme weather events, sea-level rise, and wildfires [160].

Drawing on these efforts, various social indicators for sustainable remediation have been proposed. For instance, the SuRF-UK framework proposes several social indicators for the sustainability assessment of environmental remediation options, grouped under the following categories: human health and safety; ethics and equality; neighbourhoods and locality; communities and community involvement; and uncertainty and evidence [161]. Each of these categories includes example sub-indicators and possible lines of evidence. The indicators are also mapped against the UN SDGs.

A synthesis of social indicators for sustainable environmental remediation as proposed in different countries by scholars and practitioners [162] highlighted 11 social indicators, out of which ten are relevant for the evaluation of remediation strategies including health and safety of workers and the surrounding community, economic vitality, benefits for the community at large (e.g. improved quality of life), undesirable community impacts (e.g. noise and traffic), social justice (e.g. increased household availability), the value of ecosystem services and natural resources capital, risk-based land management and remedial solutions to distribute additional resources, regional and global societal impacts (e.g. long-term public health, and contribution to local sustainability policies and initiatives; and one indicator pertains to the environmental remediation process as a whole: stakeholder collaboration [162].

IAEA in [164] mentions that social goals and values may include, among others, “full employment, preservation of cultural, economic and archaeological resources, preservation of traditional patterns of land use, preservation of spiritual values, quality of life factors, biological diversity, sustainability, protection of public health”.

A review made in Ref. [163] showed, however, that social indicators other than human health and safety are included to a limited extent in existing decision support tools for sustainable environmental remediation. The concerns of affected communities are often reduced to a criterion of ‘public acceptance’ or ‘public reassurance’, which is not conducive to transparent and traceable decision-making. There is thus a need for the operationalization of social sustainability indicators such that they can be used in decision-support tools.

Concerning the economic impacts, several aspects can be considered before, during and after the remediation process. The SuRF-UK framework, for instance proposes, indicators related to direct economic costs and benefits; indirect economic cost and benefits; employment and employment capital; induced economic costs and benefits; project lifespan and flexibility [161]. In SCORE [138], economic sustainability is assessed as the net present value. It is argued that inclusion of positive economic externalities may, at least in urban areas, balance the often-large costs associated with remediation [157].

Sustainability principles can be integrated during any phase of a remediation project, although the benefit may vary depending on the point at which they are integrated. In many instances, the benefit will be greatest when sustainability principles are integrated early in the project life cycle. For example, if sustainability principles are considered when selecting a remedial action, the benefit will be accrued through the implementation of the action. Once the action has been implemented, changing conditions or new information may prompt adjustments that will enhance the sustainability of the remedy moving forward [166].

To this end, sustainable remediation can take advantage of 'Adaptive Management’, which is a decision-making process that encourages flexibility, allowing adjustments to be made in response to uncertainties as a better understanding of the outcomes from environmental remediation and management actions, as well as other events, is gained [165]. Central to Adaptive Management is the need to learn from past outcomes of management practices and apply that knowledge to shape future operational policies and practices.

A crucial aspect in remediation processes is to identify the preferred end state or future use of a site at the outset of remediation to develop appropriate plans and strategies for streamlining the project [166]. The process of identifying the end state or future use has to consider regulatory requirements, stakeholder concerns and preferences, and the integration of sustainability principles.

Insights from practice are provided by a study among remediation practitioners in UK and USA which identified barriers and enablers of sustainable practices in environmental remediation [167]. This highlighted that organizational policy has a significant positive effect on reducing environmental impact, resource usage, and remediation cost and time. The most influential external factor was customer competitive pressure, while perceived stakeholder influence, especially that of primary stakeholders (site owner, regulator, and primary consultant), had a minor impact. Interestingly, the study showed that while both USA and UK practitioners adopt several sustainable practices, the US adopts innovative *in-situ* remediation more effectively, while the UK seems to favour the reuse, recycling, and minimization of material usage more effectively.

6.2 INTEGRATING SUSTAINABILITY INTO REMEDIATION PROJECTS

The Sustainable Remediation Forum United Kingdom (SuRF-UK) has been briefly introduced in section 5.3.8. As it provides a largely applied and very comprehensive perspective on sustainable environmental remediation, it is discussed in further details in this section.

To address the inconsistency in integrating sustainability principles into remediation projects, a framework was established by SuRF-UK to "to embed balanced decision making in the selection of the remediation strategy to address land contamination as an integral part of sustainable development"[6]. SuRF-UK is an initiative of the CL:AIRE network, which raises awareness and pursues shared land, water and environmental management objectives by collecting strategic industry information and developing industry initiatives that improve efficiency and save money. In line with CL:AIRE, SuRF-UK defines sustainable remediation as: "the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact and that the optimum remediation solution is selected through the use of a balanced decision-making process" [168, 169].

SuRF UK is a member of the wider international initiative - the International Sustainable Remediation Alliance (ISRA). This includes SuRF US and many other SuRF initiatives.

SuRF-UK is an example of a decision support framework developed for 'conventional' remediation projects that are directly relevant to 'nuclear' equivalents. It promotes the use of sustainable practices during the investigation, construction and remediation stages. It also developed the indicator framework below for option assessment on UK remediation projects. Guidance from a range of sources has been linked for 'tiered' application in qualitative, semi-quantitative and quantitative contexts. Several case studies have been published[7].

SuRF-UK provides an extensive database of indicators, organized in headline categories, each of which containing several sub-indicators. The headline categories are listed in Table 7 and each headline and sub-category has been mapped to the UN SDGs in the SuRF-UK reports.

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[6] https://www.claire.co.uk/framework-and-guidance-2/objectives-of-surf-uk

[7] https://www.claire.co.uk/projects-and-initiatives/surf-uk

TABLE 7. SUSTAINABLE REMEDIATION FORUM UNITED KINGDOM HEADLINE CATEGORIES FOR SUSTAINABILITY INDICATORS

Environmental	Economic	Social
ENV1: Emissions to air	ECON1: Direct economic costs and benefits	SOC1: Human health and safety
ENV2: Soil and ground conditions	ECON2: Indirect economic costs and benefits	SOC2: Ethics and equity
ENV3: Groundwater and surface water	ECON3: Employment and employment capital	SOC3: Neighbourhoods and locality
ENV4: Ecology	ECON4: Induced economic costs and benefits	SOC4: Communities and community involvement
ENV5: Natural resources and waste	ECON5: Project lifespan and flexibility	SOC5: Uncertainty and evidence

6.3. THE SUSTAINABLE CHOICE OF REMEDIATION FRAMEWORK

The SCORE framework, Sustainable Choice Of Remediation, briefly introduced in session 5.3.2 above, was developed and applied in Sweden to support sustainability assessment of remediation alternatives [138]. As it addresses in detail all pillars of sustainability in the context of sustainable remediation, it is discussed in more details in the following.

SCORE provides a multi-criteria decision analysis with the opportunity to account for uncertainties in the assessment. The schematic representation of decision-supporting role of SCORE within the environmental management process is shown in Fig. 1. (adapted from [138]). The framework was applied in a contaminated site in Sweden. Each social and environmental indicator (see Table 8) is assigned a score, representing expected effects relative to a reference alternative. All indicators and cost-benefit items are assigned statistical distributions representing the uncertainties of the assessments. The default setting of SCORE is to give equal weights to the three sustainability dimensions, but different weighting perspectives can be integrated.

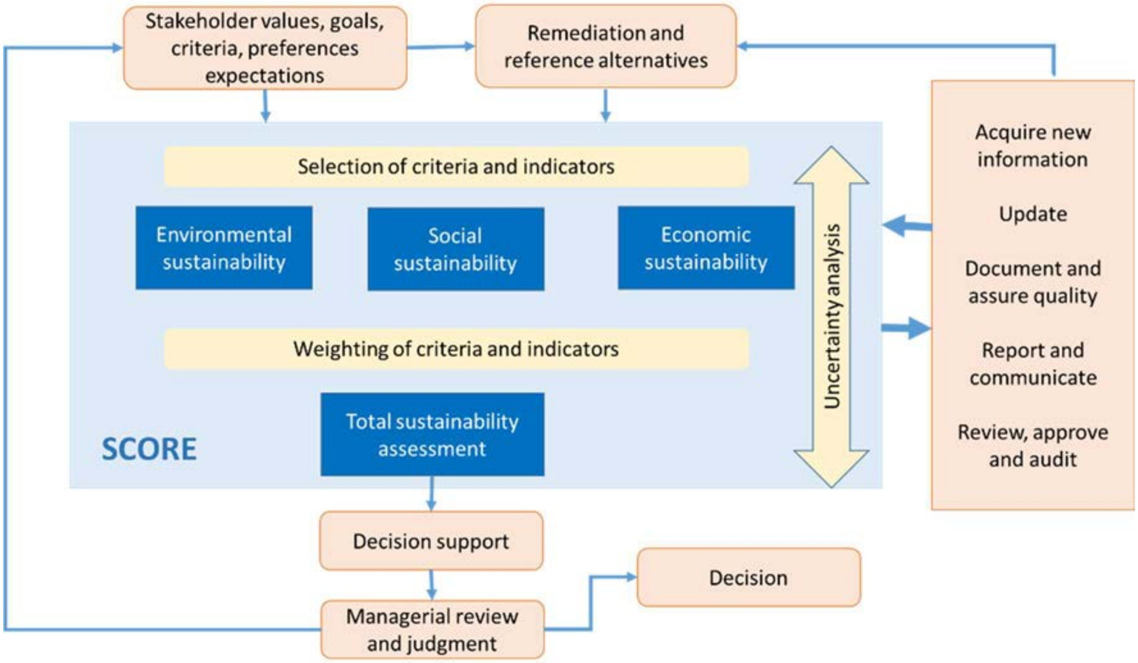

FIG. 1. Schematic Representation of the decision-making process including SCORE.

TABLE 8. KEY CRITERIA USED IN THE APPLICATION OF THE SCORE FRAMEWORK TO A CASE STUDY IN SWEDEN [170]

Environmental Dimension	Social Dimension	Economic Dimension
Soil	Local Environmental Quality and Amenity	Economic profitability as measured by net present value (NPV) in a cost-benefit analysis
Physical impact on flora and fauna	Cultural Heritage	
Groundwater	Health and Safety	
Surface Water	Equity	
Sediment	Local Participation	
Air		
Natural Resources Waste		

It was concluded that results coming from full sustainability assessments using SCORE led to remediation alternatives that balance trade-offs [157]. These results are often different from those that weigh the different dimensions unequally and/or ignore some of the sustainability indicators. Their study used a full SCORE sustainability assessment as the base scenario (all criteria included and equal dimension weighting), as well as four constructed scenarios:

— The 'private perspective', characterized by a focus on the economic dimension and ignore economic externalities;

- The ‘public perspective’, with a focus on the social and environmental dimensions and give little weight to remediation cost;
- The ‘traditional scope’, with a focus on positive outcomes on environment and health due to contaminant removal, but ignore secondary effects of the remediation activity, wider social aspects or economic externalities of the remediation;
- The ‘green scope’, including regional and global secondary environmental effects of remediation; carbon emissions, use of non-renewable natural resources, and waste production, but ignoring wider social aspects or economic externalities.

The results obtained in the four scenarios above showed that an important trade-off is between the extent of contaminant removal and the negative secondary effects, such as emissions of pollutants to the atmosphere and waste disposal. Lack of consideration of secondary environmental effects can lead to high costs and large emissions to the environment. It also showed that ‘green’ and ‘traditional’ assessments “miss out on relevant social and local environmental secondary effects which may ultimately be very important for the actual decision in a remediation project” [157].

It is therefore recommended that sustainability assessments include all three sustainability dimensions, both from a private and a public point of view.

6.4. SUSTAINABILITY FRAMEWORK FOR LEGACY MINING SITES

A sustainability framework was developed for legacy mining sites, with a three-layer structure containing principles, criteria and indicators [171]. In MCDA terminology, these correspond to dimensions, objectives ad criteria/indicators.

The indicators proposed are in majority local in nature. It is also pointed out that properties for good indicators include measurability, analytical and scientific soundness, policy relevance and sensitivity to change, being comprehensible and ethical.

The framework includes economic, environmental and socio-political dimensions. Environmental objectives are related to conservation of biodiversity on-site (8 indicators), rehabilitation (11 indicators), land condition (5 indicators), off-site impacts (7 indicators). Socio-political objectives refer to land use planning (6 indicators), legislation (5 indicators), ownership (3 indicators), responsibility (4 indicators), cultural issues (3 indicators) and health and safety (3 indicators). Finally, economic objectives relate to equitable wealth sharing (3 indicators), productive land use (5 indicators), local economic contribution (4 indicators) and cost of rehabilitation (4 indicators).

6.5. COMMUNITY-BASED APPROACHES TO SUSTAINABILITY ASSESSMENTS

Sustainable development has been broadly defined from the perspective that “humanity can make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” [172]. Scholars have questioned this definition in the latest years, pointing out its oxymoronic[8] nature [173]; its application mostly to address local, rather than global sustainable development challenges [174]; as well as its needs-based underlying paradigm. The latter triggered the development of community-based development approaches.

The term ‘community’ does not benefit from a strict delineation, e.g., geographical; it would need instead to be dynamically understood [175]. Communities are indeed complex and not solely formed based on some homogeneity property [176, 177]. In our globalized world, communities have therefore

[8] A figure of speech in which apparently contradictory terms appear in conjunction.

to be understood within their socio-political context, with due attention to the power dynamics and the involvement of vulnerable groups.

The community-based approach lies at the heart of the contestation of the local versus global approaches for sustainable development. Although the argument formulated in Ref. [174] still stands, a community-based approach to sustainability does not exclude a global view on the issue. One might even argue that community-based efforts are only truly sustainable if they incorporate a global approach or co-tackle global challenges.

Furthermore, communities can play an active role in community development [178], therefore also in environmental remediation projects, by identifying, connecting, and mobilizing existing assets. In the case of environmental remediation projects, an asset-based approach may provide valuable insights that, when accounted for, contribute to community resilience and the long-term sustainability of remediation options [179].

A prominent approach providing a comprehensive 360-degree examination of potential assets is the Community Capitals Framework (CCF). This connects assets with seven capitals [180]:

- Natural capital, including environmental components such as weather, geographic isolation, natural resources, amenities, and natural beauty [181, 182];
- Cultural capital, including elements such as experiences, behaviours, traditions and language [183, 184];
- Human capital, i.e., demographic aspects, as well as "skills and abilities of people to develop and enhance their resources and to access outside resources and bodies of knowledge to increase their understanding, identify promising practices, and to access data for community-building" [180, 185, 184];
- Social capital, i.e., connections between people and organizations [180, 186, 187];
- Political capital, e.g., ability to influence resource distribution; connections to people or organisations who can influence decisions; or citizen engagement mechanisms [180, 184];
- Financial capital, e.g., financial resources available for community capacity-building and development [188];
- Built capital, e.g., buildings, infrastructures.

The aforementioned arguments from sustainability sciences concerning community-based and asset-based approaches shows that CCF provides useful inputs for the sustainability assessment of environmental remediation projects. To this end, CCF helps identifying the resources available in a community, including technical (e.g., ancillary technologies), natural (e.g., forests, rovers), social (e.g., social networks, stakeholders), human (e.g., knowledge of traditional agricultural practices, specific skills), cultural (e.g., experience with past remediation, risk perceptions), political (e.g., access to decision making) or economic resources (e.g., possibilities to carry negative impacts). Moreover, remediation processes that build on the strong capitals of a community might create new opportunities and influence in a positive way other capitals, through a 'spiralling-up' process [180].

6.6. TAKE-AWAYS FOR SUSTAINABILITY CONSIDERATIONS

The main messages that deserve to be highlighted in this session are:

- There is a shift from sustainability as a criterion to sustainability as an overall framework for optimization (in the broader sense, including radiological and non-radiological criteria);
- Sustainability provides a common framework for decision-making, from strategic to detailed level;
- Sustainable remediation intends to maximize the net environmental, social, and economic benefits in the scope of contaminated site remediation;
- Full sustainability assessment aims to provide balanced trade-offs between the economic, environmental and social dimensions;
- Sustainability assessments have to consider regional, as well as local impacts and the cumulative impacts and opportunities across multiple sites;
- Applications in the non-nuclear fields provide several frameworks and tools that have been developed for sustainability assessment of environmental remediation that can be adapted and tested for environmental remediation of radioactively contaminated sites;
- Novel approaches to sustainability assessments, based on community capitals, support the assessment of resources available in a specific community, the available technology, the social acceptance of remediation and the economic strengths of a community.

7. CONCLUSIONS

As it has been discussed in this publication the approaches used for making decisions on the remediation of contaminated sites have changed over the last decades, as shown in Fig. 2.

FIG. 2. Evolution of decision-making approach in the nuclear field.

Choosing the optimal remediation measures for a site (especially a complex one) is a multifaceted and demanding task within the decision-making process. As illustrated throughout this publication, particularly in the case studies, the actions carried out in the scope of remediation have social, economic, environmental and ethical implications.

In the past decades, increased recognition has been given to the importance of three key aspects:

- Integration of the social, environmental and economic sustainability considerations;
- Participation of stakeholders in the decision process;
- The need for improved decision-support frameworks and tools that support the integration of the sustainability dimensions in a structured, balanced and participatory way.

Currently there is no common, integrative framework that accounts for all these three key aspects. This is currently addressed in the scope of MAESTRI.

Additionally, the review of the state of the art on the main aspects related to decision-making regarding remediation projects conducted in this publication, shows that the social and ethical dimensions are underdeveloped in terms of clear frameworks and indicators that can be used in decision-making tools. It is observed that the frameworks developed for sustainable environmental remediation in non-nuclear fields provide useful insights. Several approaches to operationalize the social impacts have been proposed within conceptual frameworks for sustainable environment management developed in non-nuclear areas relevant to environmental remediation (e.g., community capitals framework, SuRF-UK). These will be reviewed in detail, adapted and tested for their potential application to environmental remediation in the nuclear field. It is also worthwhile to study the experiences from other, international benchmark projects.

Furthermore, there is a need to foster the use of decision support frameworks and tools that can identify and take into account, in a balanced way, all the technical, economic, social and environmental aspects to be considered for sustainable and effective environmental remediation. This requires interdisciplinary approaches and the involvement of stakeholders. In this context, multi-criteria decision analysis (whether quantitative or qualitative) offers an integrative and structured framework that can accomplish the aforementioned aims. It enhances transparency since all criteria are expressed in their original form and preferences are directly included in the decision-making. However, there is a need to provide clear and accessible guidance on specific methodological aspects, as well as modalities for enhanced interaction with stakeholders in, and through, MCDA exercises. Working on the clear expression of the process (and the results obtained is a way to hope for confidence in this process. This is also a focus of the MAESTRI project.

In response to these needs, current and further work within the MAESTRI project therefore addresses the following objectives:

- Development of an integrative framework based on social multi-criteria evaluation, as well as existing sustainability assessment frameworks, with the aim to help decision-makers and stakeholders to co-develop sustainable environmental management solutions from a holistic perspective, taking into account the plurality of dimensions and values to be considered.
- Development of clear guidance explaining the main elements of the framework and ways to integrate stakeholders' values and preferences;
- Development and testing of sustainability criteria and indicators, with particular focus on the social dimension;
- Engaging the community of practice in case studies, training courses and validation exercises.

APPENDIX I

DECISION-MAKING WITHIN THE WISMUT ENVIRONMENTAL REMEDIATION PROJECT (GERMANY)

I.1. INTRODUCTION

For almost 30 years now, the federally owned Wismut GmbH has been remediating the legacies left behind by intensive uranium mining and milling operations through the former Soviet-German stock corporation SDAG WISMUT, in eastern Germany. Within complex and long-lasting projects such as the WISMUT Environmental Remediation Project, decision-making is a challenge for all parties involved. The fact that uranium mining took place in densely populated regions has also an influence on the decision-making process within the WISMUT project, since those directly affected, primarily the local population in the former mining regions, have a great interest in sustainable remediation. And then there is the fact that legal conditions change during a long-term project. How all this has been guiding the decision-making process at the WISMUT sites will be described and explained in the following.

I.2. BACKGROUND AND SCOPE OF THE WISMUT ENVIRONMENTAL REMEDIATION PROJECT

From 1946 to 1990, the SDAG WISMUT corporation produced 231,000 metric tons of uranium and became with it the world's fourth-largest uranium producer at that time. Due to the mining of low-grade ore, about 800 million tonnes of waste rock material, radioactive sludges and overburdened material were deposited at the sites. Mining and milling took place in a densely populated area, whereby radioactive waste rock piles and tailings management facilities were placed close to residential areas. The mining and milling activities resulted in seriously affected and devastated areas of about 10 000 km² in the federal states Saxony and Thuringia, in East Germany.

In 1990 after the German reunification, uranium production was ceased, and the German government was faced with one of its largest ecological and economic challenges because WISMUT turned at once from the production to the decommissioning phase without any preparation or preplanning. Since 1991 the national corporation Wismut GmbH has been charged with decommissioning the mines, mills and other facilities and with the rehabilitation of the sites. The WISMUT Environmental Remediation Project was launched. The overall project includes abandonment and flooding of underground mines, relocation and covering of waste rock piles, dewatering and geo-chemical stabilization of tailings management facilities, demolition of structures, treatment of contaminated water, site clearance and site rehabilitation.

At the Schlema site, for example, most of the waste rock piles are remediated in place. Major remediation phases include regrading of slopes, capping with a cover consisting of 0.8 m inert material and an overlying layer of 0.2 m topsoil, and seeding for revegetation (Fig. 3). In terms of complexity and size, the WISMUT Environmental Remediation Project is unique, even by international standards. The project involves remedial activities at sites located at a considerable distance away from the Wismut headquarters in Chemnitz, e.g., the Aue site 40 km away, or even 100 km away Königstein site.

FIG. 3. Contouring and coverage of a big waste rock pile in Schlema-Alberoda (Aue site).

I.3. DECISION-MAKING UNDER THE WISMUT PROJECT

The WISMUT Project for remediation of uranium mining and milling legacies is also unique in its time dimension. Ongoing for almost 30 years, current plans predict completion of the physical work (covering the tailings ponds) by 2028. The subsequent implementation of long-term activities (mainly environmental monitoring, water treatment and object-specific aftercare measures) will take decades. In such long-term projects, the decision-making process also goes through various phases, with different decision-making priorities (Fig. 4).

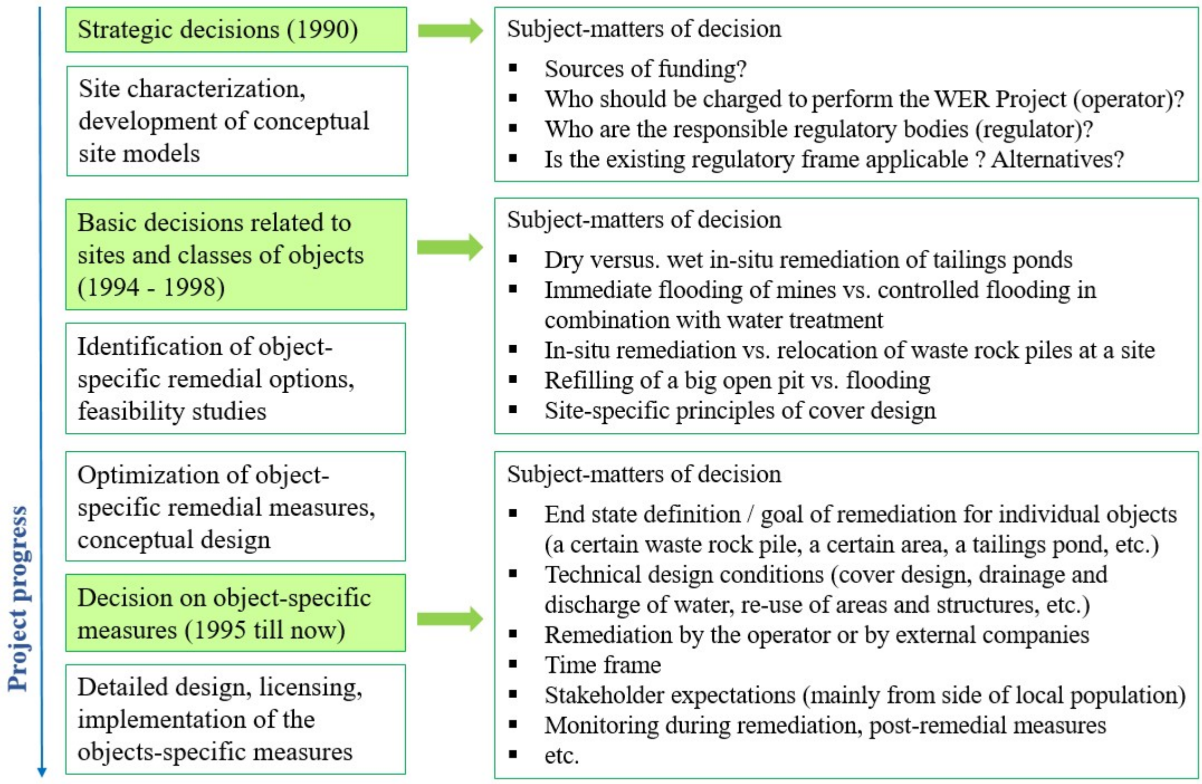

FIG. 4. Decision phases within the WISMUT Project course.

I.3.1. Strategic decisions (1990)

Strategic decisions had to be made on the governmental level right before the commencement of the WISMUT Project. As a result, for project funding, the German government initially earmarked a total of € 6,4 billion to rehabilitate the uranium mining and milling legacy at the affected sites. Recent estimates arrive at total project costs of € 8 billion.

The newly founded Wismut GmbH was largely recruited from personnel of the former SDAG WISMUT. The decision to transfer the project responsibility to these persons was not undisputed, mainly because of the distrust of the population towards former SDAG staff. However, due to the complex expertise required to manage the project, there was no alternative.

The authorities of the two federal states concerned, Thuringia and Saxony, were designated as responsible for the approval and supervision of the remediation under the WER Project. As there was no suitable legal framework in the old German Federal Republic to regulate such a complex project of remediation of uranium legacies sites, it was decided to apply the radiation protection law of the former German Democratic Republic, which corresponded at that time to international standards. The application of GDR law was terminated only by end of 2018.

I.3.2. Basis decisions related to sites and classes of objects (1994 – 1998)

The German Brenk Systemplanung GmbH in its function as a consultant to the German Federal Ministry for Environment used for basic decisions an approach to the cost-benefit analysis which was primarily based on the determination of the collective dose and the number of harm events deduced from risk factors (e.g., cancer incidences, loss in life expectancy). The amount of harm was monetarized by comparison with the amount of cost that society would be prepared to pay to attain a certain degree of harm reduction (described by what is known as the alpha value). The identified optimum rehabilitation option was the one that cut the sum of remediation costs and harm-equivalent costs down to a minimum. At a later stage when taking an integrated approach, the BRENK Systemplanung GmbH also included non-radiological risks into the cost-benefit analysis. Thereby, risks arising from the incorporation of carcinogenic substances like arsenic or organic contaminants were considered. Based on the risk estimates, the mean losses of a lifetime were assessed and monetarized for the collective intake of the non-radiological hazardous substances by a cohort. In the same way, potential losses of a lifetime due to work and transport accidents during remediation activities were taken into account.

A pure cost-benefit analysis conducted along these lines does not go undisputed, primarily because of the uncertainties of intermediate results (problem: calculation of realistic collective doses and intakes) and of the assumptions to be made (amount of the alpha value; integration period for the post-remedial condition [200 or 1,000 years?]; application of dose cut-off criteria, etc.). Although the use of collective doses computed by the summation of smaller doses of a large population group is not recommended by the ICRP in their basic Publication 103 issued in 2007, the procedure used by BRENK Systemplanung at that time has proven its worth as a useful tool in deriving fundamental decisions for sites and classes of objects. Cost-relevant parameters were more easily identified, and decision-making became more transparent. The cost-benefit analysis was also applied as a sensitivity analysis tool. This was done within an approach whose core element was the consideration of probability distributions for the input parameters of the cost-benefit analysis and a Monte Carlo simulation based on this.

In preference to a purely cost-benefit analysis, already in the nineties, WISMUT started to successfully apply a multi-attribute analysis which in addition to costs also considers what is known as soft factors such as social factors, aspects of licensing and planning regulations, or acceptance issues – which in the broader sense means involvement of all stakeholders (see the following section). The inclusion of these factors increased the acceptance of both, the basic decision as well as the later object-related decisions.

I.3.3. Object-related decisions (1995 till now)

Based on experiences already gained during the basic decision phase, WISMUT developed within the object-related decision phase its approaches to the multi-attribute analysis further. This was necessary because the company increasingly had to recognise that the development and approval of technically feasible and at the same time sustainable remediation solutions requires consideration of regulatory, technical and socio-economic conditions. In other words, the involvement of stakeholders became an important element in the decision-making process.

A simple approach was (and continues to be) the development of decision matrices for different remedial options (alternatives), whereby scores s_{ij} (e.g., running from 1 to 5) were allocated to each option i and attributes A_j weighted by factors of w_j (with a sum over all w_j equal to1). The option maximising ($\sum A_j w_j s_{ij}$) stands for the preferred remedial option. For example, Typical attributes for identifying the best-suited option for in-situ remediation of a large waste rock pile near to a residential area were *inter alia*:

- Remediation costs;
- The technical effort required for contouring and covering;
- Near-by availability of cover material;
- Dust and noise during remediation;
- Remaining environmental impact after remediation (through radon, seepage water, etc.);
- Long-term geotechnical stability of slopes and the surface;
- Sustainability of the option;
- Costs for post-remedial surveillance and maintenance;
- Possibilities for re-use of the surface;
- Integration of the contoured, covered and re-vegetated pile into the local landscape;
- Acceptance of the remedial option by the local public;
- Potential problems for getting a license (i.e., acceptance on the side of the regulator).

The weighing of attributes and allocation of the scores depend strongly on the person who makes the respective evaluation. The evaluation results may therefore inhibit subjective character. This can be countered by a clear definition of what is meant by the criteria. For example, Wismut did not only consider sustainability in the sense of the long-term preservation of an achieved condition but also in the sense of opening up horizons for the subsequent use of the renovated properties.

Another example is the acceptance of the remedial by the local population. Of course, a remediated object which does not fit with its final contour into the landscape will not be accepted by the locals. Object-specifically, non-acceptance may even become a knock-out (veto) criterion for a certain remedial option. The question, however, whether an option is accepted or not, can at the end of the day only be answered by the locals themselves.

That is why the results of the identification of the remedial options for large complex objects have been and are still being subject of discussion with stakeholders. Remediation plans have been made available to the public. Residents, the municipality and other parties directly affected by the remediation have been allowed to raise objections to remediation solutions. An example of a successful intervention is a remediation of the waste rock pile #66/207 in Schlema-Alberoda. Following demands by the inhabitants of buildings immediately neighbouring the pile, Wismut GmbH had to revise the construction plans for reshaping and covering pile #66/207. Initially, the remediation plan for this object was solely focused on the goals of reducing radon releases and minimizing the infiltration of precipitation into the waste rock body. The inhabitants required in addition a final counter which enables a better view towards the Schlema village. Following this, Wismut GmbH had to amend the remediation plans and spent more money for the re-shaping of the pile.

To facilitate the involvement of stakeholders, at each WISMUT site regular meetings with representatives of the municipalities take place. At the Königstein site, an environmental advisory board ('Umweltbeirat') was established, in which representatives of different stakeholder groups discuss every year the progress of remediation and plans for future activities at the site.

I.4. CHALLENGES ENCOUNTERED IN THE DECISION-MAKING PROCESS

Two challenges deserve to be highlighted: decision-making for remediation in densely populated areas and regaining the trust of the population towards WISMUT.

I.4.1. Remediation in densely populated areas

Decisions on rehabilitation measures in densely populated areas pay particular attention to the following aspects:

1. The immediate proximity of the remediation place to residential areas and other areas highly frequented by the population requires increased technical effort to minimize negative impacts on the health and living conditions (dust, noise, etc.) of the population during the remediation and to achieve the remediation target in the long-term;

2. In addition to the legally prescribed objectives of the remediation, the interests of the residents have to be taken into account, e.g., about landscape design and the subsequent re-use of rehabilitated areas.

Point 2 leads back to the need for stakeholder involvement.

The challenge 'remediation in densely populated areas' becomes obvious from Fig. 5.

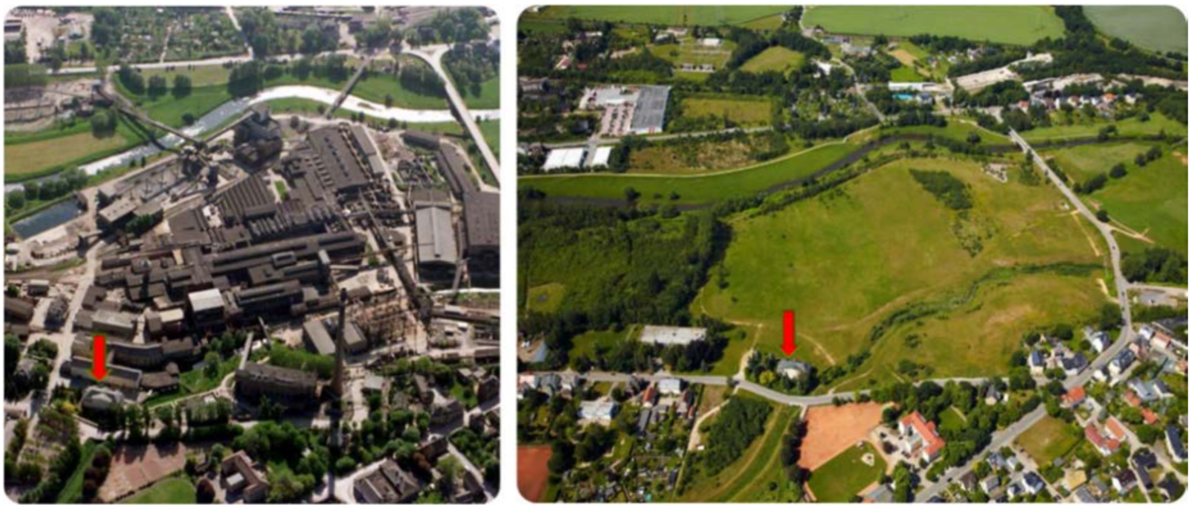

FIG. 5. Area of the former uranium processing plant in mid of the Crossen town before remediation (1991) and after (2011).

I.4.2. Building bridges with the public

Uranium production in Germany was carried out under conditions of military organization and in utmost secrecy. Production perturbed living conditions of the population and disturbed landscapes. Accordingly, there was a great degree of distrust among the public towards the newly founded Wismut GmbH in 1990 immediately after German reunification.

The new management of WISMUT was fully aware that coping with the large-scale environmental restoration project necessitated acting in concert with the general public and other stakeholders.

‘Building Bridges with the Public’ was adopted as the company’s corporate policy. Over the years, various forms of building bridges have evolved. In that context, the following measures deserve emphasis without any claim to completeness:

- Development of site and object-specific remedial concepts giving priority to re-use options of objects/areas for the benefit of the local population;
- Stakeholder involvement in decision-making on choosing remedial options and solutions for the safe disposal of radioactive materials and residues;
- Unrestricted stakeholder access to all environmental data, comprehensive information on environmental impacts;
- Active involvement of local firms and engineering consultants in the remediation project (job creation opportunities);
- Annual environmental reports, annual ‘Miners Day’ and ‘Open House Days’ events; preservation of mining heritage and traditions, WISMUT exhibition (see Fig. 6) ;
- Scientific conferences and workshops.

The stakeholder dialogue also had and continues to have its disputatious moments. The Church Environmental Group, an NGO in Ronneburg, for instance, has accompanied remedial operations by Wismut GmbH right from the beginning, by challenging remediation decisions made by Wismut GmbH. WISMUT readily gets into a debate with the Group, gives routinely presentations and performs also radiological field measurements along with members of the Group. Their critical dialogue is beneficial to both parties. On the one hand, citizens get first-hand professional information. On the other, WISMUT benefits from being obliged to explain its remediation decisions in a non-technical way that can be understood by the average citizen.

FIG. 6. Impressions of the open house day 2017 at the Ronneburg site (5 000 visitors).

I.5. CONSEQUENCES OF THE DECISIONS

At the one site, remaining near-surface aggregations of contaminated material in form of covered tailings ponds covered waste rock piles and safely closed disposal sites cause forever restricted re-use of the affected land. Further, these objects require (also forever) surveillance and maintenance. During decision-making these potential burdens for the life of future generations had to be weighed against the implementation of extremely expensive and technically hard to manage remedial solutions (for instance the backfilling of mines). The only way to keep the burdens for future generations acceptable is to integrate the remediation concepts into plans for sustainable development of sites or, in other words, to open horizons for re-use.

A good example of successful integration of reclamation and town re-development is provided by Schlema, where recreational facilities, such as the health spa, parks, promenades, even a golf course, were established on a backfilled, rehabilitated and stabilized mine subsidence area and on rehabilitated waste rock piles (see Fig. 7).

FIG. 7. Aerial view towards the Schlema spa garden, with re-shaped, covered and re-cultivated waste rock piles on the left.

Before the Second World War, Schlema was a famous radon spa where people from many European countries recovered and healed mainly rheumatic diseases. The re-birth of Schlema as a spa (since 2005 Bad Schlema) gives evidence that the WISMUT word 'New Horizons Through Remediation' is more than just a slogan.

I.6. LESSONS LEARNED

Looking back on almost 30 years of implementation of the WISMUT project and with the experience gained during this time, the following three recommendations are formulated:

- Instead of purely cost-benefit analysis, multi-attribute analyses might be applied for decisions in the context of complex rehabilitation projects;
- Stakeholders have to be involved in the decision-making process at an early stage;
- The optimization of remediation measures is often a complex and demanding task within the decision-making process. It is worthwhile to study the experiences from other, international benchmark projects. The recommendations and case studies, disseminated by the IAEA, e g. within projects like MAESTRI, are helpful in the study.

APPENDIX II

APPLICATION OF A MULTI-CRITERIA ANALYSIS METHODOLOGY FOR THE REMEDIATION PLAN OF A POUND IN MALVEZY SITE (FRANCE)

II.1. INTRODUCTION

The case study is related to the management of the regulation basin of the Orano site in Malvezy (near Narbonne, France). ORANO conducts soil remediation activities on its industrial sites and at different stages of the life of its Basic Nuclear Installations (henceforth, BNI): accidental leakages during operation, confinement or treatment of historical pollution, clean-up before and during dismantling. Soil remediation activities along with the clean-up of the facilities and structures are integral parts of ORANO's dismantling strategy. Orano is working on the development of a specific methodology to guarantee the rigorous and homogeneous treatment of this issue for all its projects. The paper aims to describe the degree of achievement of this methodology and how its application to case studies allows, on one hand, to strengthen the methodological aspects and on the other hand, to improve some of them.

From 1959 to 2008, COMURHEX[9] and SLMC[10] operated a regulation basin (BR) of approximately 1.5 million m^3 of water for the discharge of their industrial and storm waters and the recycling of cooling water. This period of operation resulted in the accumulation of approximately 60,000 m^3 of sludge at the bottom of the basin containing approximately 260 tonnes of metals (cadmium, copper, zinc, uranium and mercury, among others). Chemical and thermal stratification of basin waters has been well established and allowed to maintain reducing conditions in deep waters that constitute geochemical containment of metals in sludge. Since January 2008, the BR is no longer used as a water outlet for the SLMC and Orano Malvezy sites. The environmental monitoring of the BR is still active, and the issue is now to build a remediation plan.

Orano and Total-Retia (which operates the remediation for SLMC) are engaged in a collaborative steering group to prepare the remediation plan and to submit it to the authorities. Several remediation scenarios were studied and four of them were selected as possible ones and submitted to the current decision-making process:

- Drag and off-site disposal (of the polluted sludge);
- Drag and on-site storage;
- In-situ drag and containment by solid materials;
- In-situ containment by water cover.

II.2. DECISION-MAKING METHODOLOGY

ORANO's methodology for soil remediation is based on the principles and guidelines established in the guide n° 24 of the French Nuclear Authority 'Gestion des sols pollués par les activités d'une installation nucléaire de base en France' [189].

The first step is to set the goal of remediation of structures and soil. First, Orano evaluates the implementation of the reference approach, which is that of complete remediation that is to say the clean-up of the soil to recover the initial conditions before any industrial activities (named in the following baseline scenario). In the event of difficulties in implementing complete remediation, Orano defines one or more 'variants' corresponding to alternative scenarios, so-called extensive or proportionate scenarios.

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[9] Former name for Orano site at Malvezy.

[10] Société Languedocienne Micron Couleur, factory which manufactured colored pigments.

The baseline scenario and variants have to be evaluated objectively and robustly to be compared and allow for the choice of the most appropriate one. The evaluation process needs also to be able to be adapted to various situations (historical pollution, dismantling, post-accidental cleaning …). In this way, multi-criteria analysis is a helpful decision-making tool in the choice of the rehabilitation scenario to be deployed.

Following the recommendations of [189], ORANO developed in 2018 a multi-criteria analysis methodology (henceforth, MCDA) based on the REX of several previous cases of sites remediation: industrial site of SICN at Annecy (France), nuclear site of SICN at Veurey-Voroize (near Grenoble, France), BNI n°105 and BNI n°93 of the Tricastin site (Pierrelatte, France). The *a posteriori* study of the above-mentioned situations of remediation allows Orano to identify the set of criteria which were used to support the remediation scenario decision [190]. Then, the same set of criteria was proposed by Orano to be used to compare remediation options for the ongoing and future projects to conduct a systematic assessment of remediation options and justification for those situations in which complete remediation was deemed to be unsuitable.

The set of criteria is as follows:

- Nuisance: noise, dust, gaseous and liquid discharges, degradation of water quality, traffic, etc.;
- Technical feasibility: existence and availability of technical means, human resources and necessary skills to implement the remediation strategy;
- Reuse of buildings: mechanical resistance of buildings, cleaning and renovation of structures and utilities, etc;
- Future uses of the site: consequences for the nearby industrial environment (buildings and grounds), sustainability of the site and future uses, etc;
- Time: estimated duration of the overall remediation project;
- Costs: direct and induced costs, contingencies and risks to be provisioned, additional financial provisions to be constituted, etc;
- Waste: nature and category of waste, volumes, existence of management protocols, pre-shipment storage conditions, packaging, transport, etc;
- Exposure of workers: risks of worker exposure to hazardous (radiological) situations;
- Safety of the workers: risks of worker exposure to hazardous (physical or chemical) situations.;
- Impact on protected interests: Residual risks or disadvantages on protected interests.

A scale of assessment from 0 to 5 for each criterion is used to evaluate each remediation option against the aforementioned criteria. A low score means a bad mark and a high score means a good one.

A Kiviat diagram (or spider radar) is a representation of the results of the multi-criteria approach that allows one to compare the advantages graphically, but also the disadvantages, of the variants of remediation (Fig. 8). The rating associated with the criteria can be generally considered through this diagram representation which highlights the scenario that has the most overall advantages. It was initially proposed that the difference between the areas of the different scenarios guides the selection of the scenario, but as illustrated later, with the case study, this point is questionable.

This method was presented by Orano at the French Nuclear Authority because it was asked to explain our whole strategy for dismantling our nuclear facilities. The French Nuclear Authority made some remarks/demands, that led Orano to keep on improving its methodology. In particular, Orano is committed to systematically justifying its choice of dismantling scenarios by presenting the difficulties of failing to retain complete remediation, in a detailed analysis structured according to the aforementioned criteria. Moreover, Orano is committed, in the future applications of its multi-criteria approach, to present and justify a grading specific to each of the established criteria.

To consolidate the method and answer to the authority requests, various actions have been taken: a review of the international literature related to multi-criteria approaches devoted to soil management [191], the expertise of the methodology by scientific experts [192] and case studies of application.

Reference [191] showed that MCDA is a well-established approach to integrate technological and scientifically based risk assessment with complex sociological risk perception by the various stakeholders. The review showed that MCDA has been broadly used in the context of environmental remediation of contaminated soils, by both international and national agencies. In most cases, the MCDA methodology has been considered very useful to integrate the trade-offs between socio-political, environmental and economic impacts and the complexity added by the different views from stakeholders.

Reference [192] reviewed Orano's proposed MCDA methodology for remediation of contaminated soil. It assessed the relevance of the criteria chosen by Orano and proposed improvements 1/in the way of assessing each criterion 2/ in the method of grading the criteria, and 3/ in the visual representation of results. [192] also discussed the application of the MCDA method, including the need to involve stakeholders in the pre-analytical process, as well as the value of a sensitivity study to test the influence of criteria and their indicators on the total performance of proposed solutions.

The next step in this case section is now to describe an application case study and to show how this case study identified biases in the method and the resulting proposals for methodological evolutions.

II.3. MAIN CHALLENGES ENCOUNTERED IN THE DECISION-MAKING PROCESS

In the application of the methodology, it appeared the need for a former step in the methodology which was to define the indicators to assess each criterion. Indeed, the criteria are very generic, which does not allow the performance of scenarios to be directly assessed. Table 9 illustrates the indicators which were used for the BR application case to assess some of the Orano methodology criteria.

This former step of fine characterization of each of the criteria was essential to allow the in-depth discussion within the framework of the steering committee and to fix the value for each indicator and then to calculate the value for each criterion. For now, the description of the indicators seems very well adapted to the BR application case but, without a doubt, it can also be useful for other remediation situations.

A grading of 1 to 3 was used indicating that an indicator is ‘not very important’, ‘important’ or ‘very important’, respectively. If an indicator is irrelevant to the application case, it has been given a grade of 0 (for example, for the Malvezy BR application, there is no building on the site, so the criterion ‘Reuse of building’ is irrelevant; it was fixed at 0). Because the number of indicators per criterion is different, the grade of each indicator has to be standardized for each criterion. Thus, the grades of the indicators, initially between 1 and 3, will be related to a fraction so that the sum of the grades of the indicators of a criterion is always the same, for example, 1. For the BR application case, it was decided to work with a 100-base and the grade of each indicator as a percentage.

While rating the indicators, two scenarios may exist depending on whether the indicator is perfectly quantifiable or not. Perfectly quantifiable indicators, such as costs, delays, volumes of treated waste, residual waste volumes, etc., allow one for the direct comparison of scenarios. Unquantifiable indicators, such as the need for administrative authorization, the sustainability of the treatment solution, or impact on flora and fauna, require the use of linguistic description (‘very unfavourable’ ‘unfavourable’, etc.) to allow qualitative comparison of the different scenarios. Both methods of rating indicators were used for the BR application case. Table 10 shows how a systematic comparison of quantitative or qualitative criteria is possible.

TABLE 9. EXAMPLE OF THE INDICATORS FOR THE CRITERION ‘NUISANCE’ AND THE CRITERION ‘COSTS.’

Criteria	Indicators	Description
Nuisance during construction	1. Impact on fauna and flora and protected areas	Disturbance of wildlife and protected areas in the vicinity of the site
	2. Nuisance in the vicinity	Generation of odours, noise, dust, an increase of traffic, wear and tear of roads and other infrastructures in the vicinity of the site.
	3. Degradation of air and water quality (surface and groundwater)	Contamination of the air and surface and groundwater resulting from atmospheric emissions, liquid discharge and runoff, changes of ground water level or surface level of ponds, solid waste production.
	4. Energy consumption and impact on climate change	Fuel and electricity consumption and greenhouse gas emission.
	5. Water and materials use	Water and materials consumption (cement, clay…) for construction work.
Costs	1. Cost of the preliminary and complimentary studies and cost of the arrangements needed before the beginning of the construction.	Cost of characterization studies, geotechnical and hydrogeological studies, emission studies, flora and fauna impact studies, and other environmental studies, laboratory tests, preparation of the draft, conducting *situ* pilot tests, processing of authorization and licenses etc.
	2. Depollution costs	Direct costs of implementing the clean-up solutions; materials and works, equipment, manpower, staff training, waste management etc.
	3. Environmental monitoring costs.	Costs associated with monitoring environmental parameters, and maintaining the site once it has been treated; geotechnical stability and geomorphological adequacy, leachate treatment, monitoring of residual contamination etc.
	4. Financial costs, risks and depreciation of costs	Amortization, interest on loans, financial risks, depreciation, etc.

TABLE 10. THE RATING SCALES USED FOR THE BR CASE.

Qualitative rating	Rating level	Cost of preliminary studies (€)	Constr. Costs (€)	Monitoring costs (30 years) Constr. Duration (€)	Constr. Duration (months)	Residual mass of pollutant (tons)	Amount of waste produced (tons)
Irrelevant criterion	0	-	-	-	-	-	-
Very favourable, Disproportionate Impossible	1	> 2 M	> 4 M	> 2.4 M	> 48	> 100	> 100,000
Unfavourable, Difficult to realize, Generate constraints	2	> 1 M	> 2 M	> 1.6 M	> 24	< 100	> 10,000
Neutral, Non-discriminatory	3	> 600,000	> 1,000	> 800,000	> 12	< 10	> 1,000
Favourable, Reasonable, Acceptable	4	> 200,000	> 500,000	> 200,000	> 4	< 1	> 100
Very favourable, Advantageous	5	< 200,000	< 500,000	< 200,000	< 4	0	< 100

II.4. CONSEQUENCES OF DECISIONS AND LESSONS LEARNED FROM THE MAVEZY BR CASE STUDY

It is difficult to state definitively about the decision (and its consequences) concerning the remediation scenario chosen for the BR of Malvezy because this choice is currently in the regulatory process which is not yet ended. However, the upgrades brought to Orano's methodology thanks to this application case will be discussed.

A significant learning of the BR case study is related to the visual way the results are represented and used to support the decision-making process.

The method currently used by Orano to compare the results of the MCDA study is based on the representation of Kiviat diagrams (see Fig. 8). Such radar graphs were found useful for presenting the performance of different criteria on the same figure and thus comparing different scenarios.

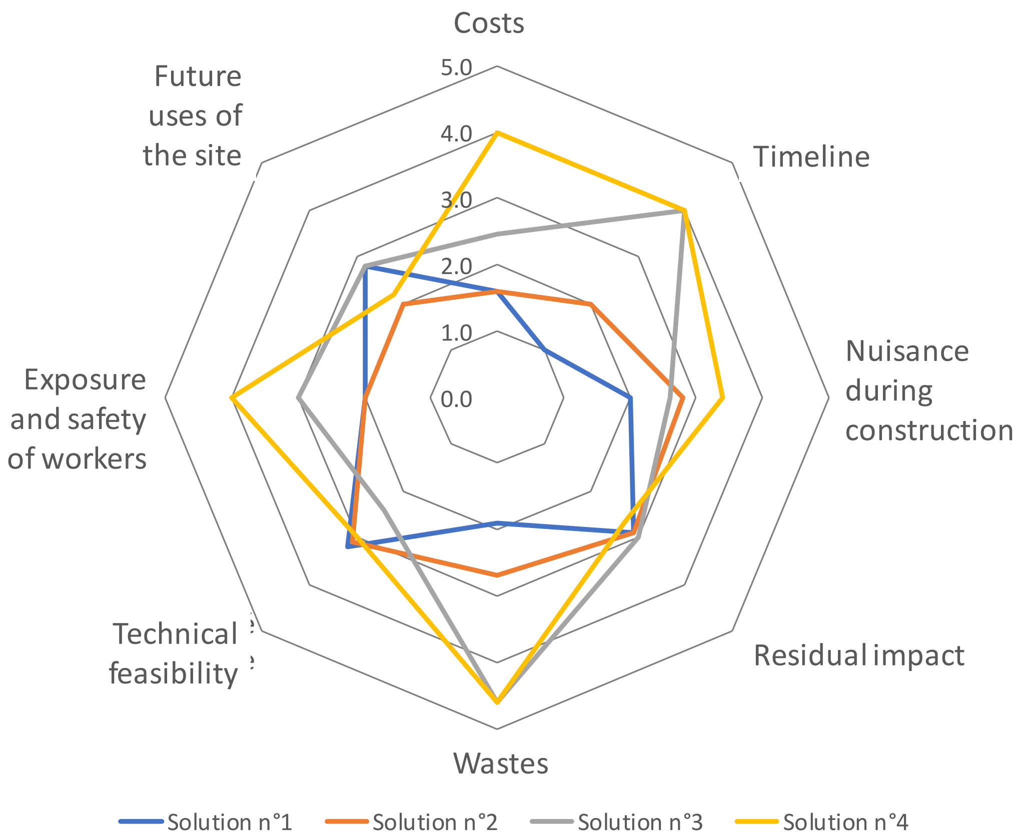

FIG. 8. The Kiviat diagram for the different scenarios of the BR remediation.

However, the use in the Kiviat diagram of lines connecting the score of each criterion generates an area which, the larger it is, the more efficient the solution seems. Thus, this representation gives a misleading assessment of the performance of the solutions because the criteria do not have a logical link between them.

II.5. LESSONS LEARNED

The application case of the BR was an opportunity to explore various formats to visualize, on one hand, the results of the multi-criteria analysis, and, on the other hand, the grading of each criterion and indicator. These representations helped in the appropriation of the results by the steering committee and therefore contribute to the acceptability of the methodology used. It was important to keep in mind that the multi-criteria tool remains complex and can be felt like a ‘black box’ for stakeholders. Working on the clear expression of the process (and the results obtained) is a way to hope for confidence in this process.

To illustrate the results of a multi-criteria analysis with a radar diagram, it is recommended that criteria are not linked to each other, so as not to visually generate a surface. A radar diagram can only give a detailed representation of the criteria taken individually but cannot inform about the overall performance of a solution. To compare the results of multi-criteria analysis, the use of several types of complementary diagrams can be useful to visualize the total performance and the influence of each criterion in each solution studied.

To help in the appropriation of multi-criteria analysis' results, it is proposed to use two possible representations: a sunbeam graph (Fig. 9 and/or a compartmentalized graph (Fig. 10). These graphs can provide a view of the relative importance given to the criteria and indicators and support an understandable debate of what was considered most important in the decision process.

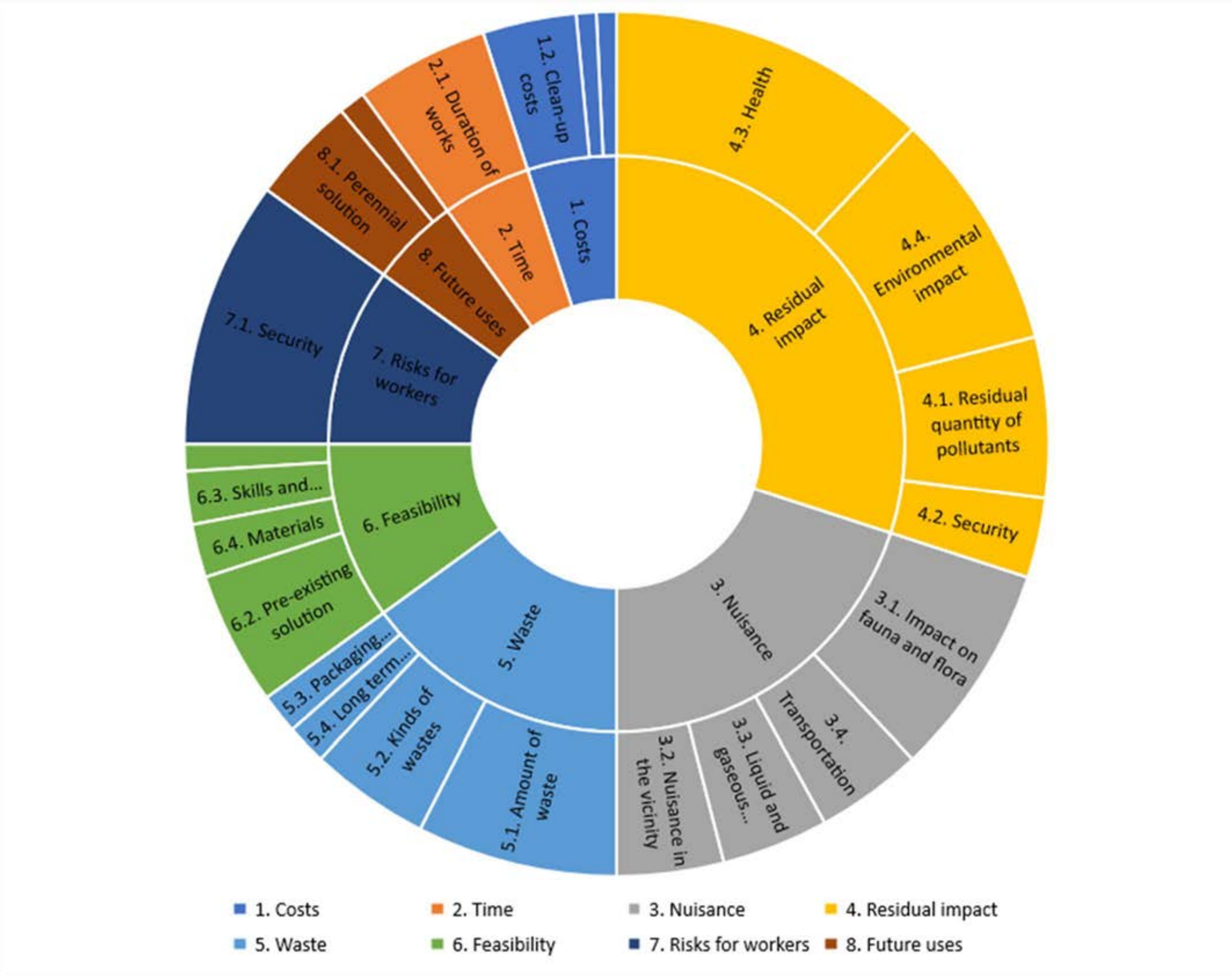

FIG. 9. The Sunbeam graph from Malvezy BR case.

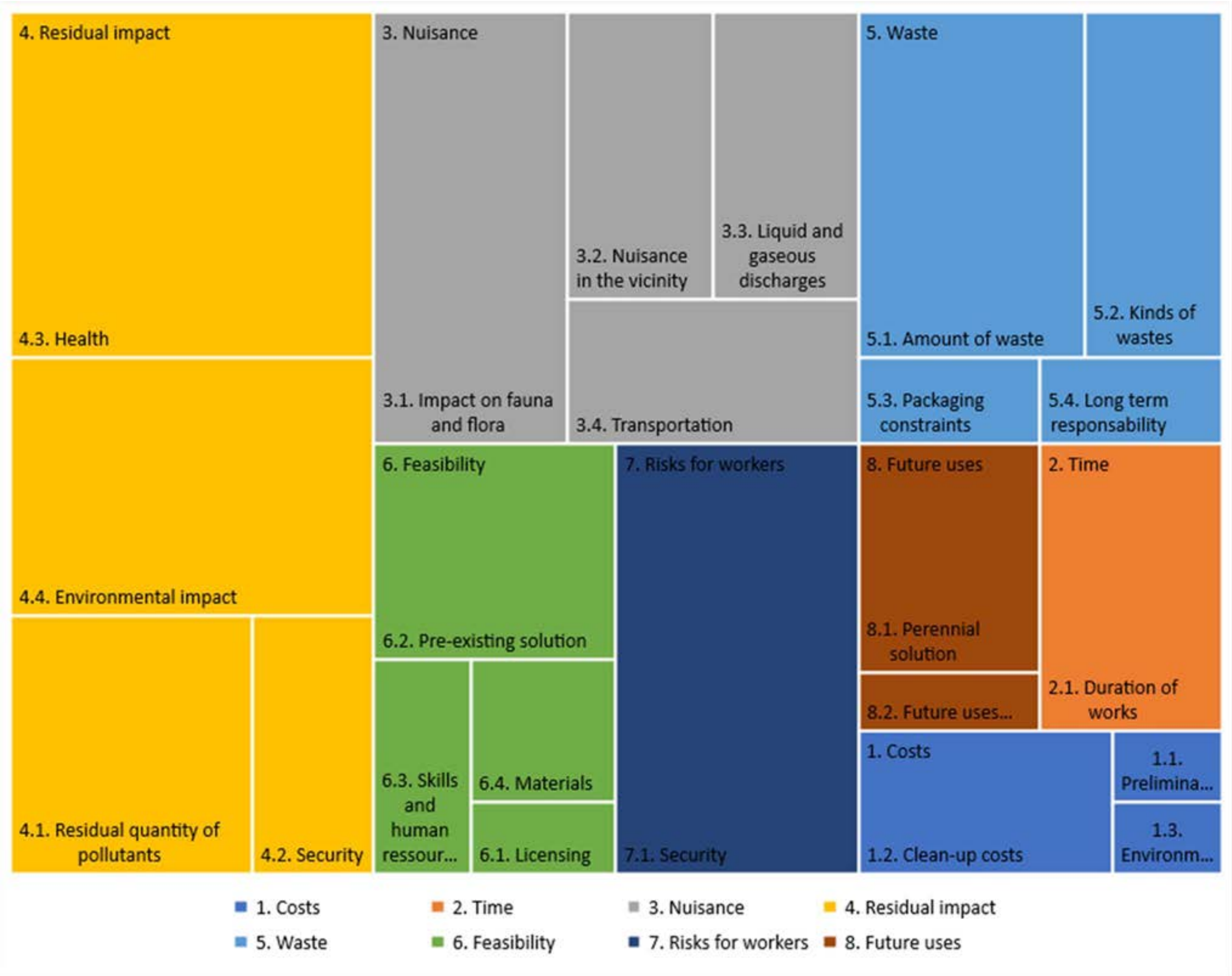

FIG. 10. The compartments graph from Malvezy BR case.

APPENDIX III

REMEDIATION OF THE URANIUM MINES OF THE SOUTH ALLIGATOR VALLEY, NORTHERN TERRITORY (AUSTRALIA)

III.1. CASE DESCRIPTION

Uranium has been mined more or less continuously in the Northern Territory of Australia since 1949. The mines have all been located on land owned by Traditional Aboriginal people. In earlier times there was little or no consultation with the Traditional Owners and little attention was paid to remediation when mining was completed. The area chosen for this case study, the South Alligator valley, was the site of 13 small uranium mining operations between 1955 and 1964. Typically mining and processing areas were simply abandoned as work ended. The valley was incorporated into the World Heritage-listed Kakadu National Park as stage Three, in 1987. In 1996 the Gunlom Land Trust was granted the area under the Commonwealth's *Northern Territory Land Rights Act (1976)* but immediately the trust leased the land back for continued use as a National Park. A condition of the lease is that all former mine sites and associated workings were to be rehabilitated by 2015.

To achieve these objectives, it was necessary to develop closure objectives and completion criteria. This in turn had to be preceded by the development and implementation of a comprehensive consultation process that involved all stakeholders. The final rehabilitation had to satisfy the requirements of all stakeholders yet still meet the objectives of the park's Plan of Management, the future plans and hopes of the Traditional Owners and all relevant regulatory requirements, including radiological safety standards.

The Pine Creek geosyncline uranium province lies between 13° and 14° south of the equator in the wet/dry tropics, (A_w in the Köppen (1936) classification). The average annual rainfall is approximately 1200mm of which more than 90% falls between 1 November and 30 April (the wet season). The temperature averages about 21°C annually with maxima often around 40°C and minima rarely below 14°C. The area is a dry savanna woodland with some sandstone escarpment country. The vegetation is generally dominated by eucalyptus species with some acacias and ironwoods in the drier places and pandanus and melaleuca species in the wetter areas.

The population of the wider area is concentrated in a few settlements, many of which owe their existence to mining operations. For example, the townships of Batchelor and Pine Creek have populations of barely a hundred, somewhat less than the days of the mining booms of the 50s, 60s and early 70s. There is an Aboriginal population in the region living in outstations as well as in the townships. However, there is no permanent population in the upper South Alligator Valley where the mine sites are located. There are seasonal camping grounds for tourists and one or two outstations used by Traditional Owners sporadically in the dry season. In the wet season roads to the area are generally impassable.

Uranium mining began at Rum Jungle in early 1950, some 100 km to the west. Exploration discovered a group of smaller mines in the upper reaches of the South Alligator valley. The valley was remote and the only acknowledged land use at the time was extensive cattle ranching in the bushland, which had begun around 1950. However, more than 50 radiological anomalies were located in the valley. Follow-up groundwork identified economically viable uranium deposits and mining began in about 1954. Details of this early history of uranium mining are well documented [193] The operations were all small by modern standards, total production between 1955 and 1964 amounted to about 850 tones U_3O_8 [193]. Development of the mines was straightforward, with no requirements for Environmental Impact Statements or consultation. The former was because there was no appropriate legislation in existence then; the latter because the local population was considered to be only the pastoralist, although Aboriginal people were present in the valley from time to time.

To undertake the rehabilitation of abandoned sites in the South Alligator valley a project was set up commencing with the development of communication systems to address the cultural and technical issues appropriately and effectively.

An initial inventory of sites was undertaken in 1986 to establish the scope of the task. As the declaration of the National Park went ahead it was decided to undertake an interim works programme in 1992 to address issues of physical and radiological safety to reduce hazards for tourists and visiting Traditional Owners. This was achieved through blocking of adits and tunnels, obstructing road access to mine pits and burial of radioactive ore and wastes, including demolition waste from three processing sites, one of which had been a small mill. It was always understood that this was an interim programme. Traditional owners were consulted on the nature of the work and participated as members of the workforce.

Following the signing of the formal lease in 1996 an initial stakeholder meeting was held in the country in October 1997. This involved bringing together many smaller Aboriginal groups as well as representatives of several government agencies, both Commonwealth and NT. This created the risk of two groups developing, Aboriginal and non-aboriginal. The use of an open-air venue with two days put aside for talking relieved much of the stress for those unaccustomed to meetings. The format was made as informal as possible whilst maintaining a structure.

It transpired that whilst the Traditional Owners knew much about the sacred sites in the valley, they were not familiar with the majority of the mining sites. Questions from the local people indicated they had little detailed knowledge of the former mining activity or the potential environmental impacts, apart from obvious visual impacts. For example, having to explain acid rock drainage was an interesting first challenge for technical experts. It soon became apparent that communication was not as effective as it might, and needed to, be.

For many of the non-aboriginal people present this was their first experience of having to deal directly with the Traditional Owners rather than through their legal representatives, the Northern Land Council. The process was far from perfect. Some of the difficulties included: inappropriate language with too many long and jargon words, representatives from different organisations wearing similar uniforms and unrealistic expectations amongst some of the non-Aboriginal people that decisions would be made soon after what seemed like complete and logical explanations had been delivered. This revealed a poor understanding of how Aboriginal communities make decisions by consensus rather than by the majority. The rate of progress was too slow for some people. The problems continued after the meeting with the production of a summary record that was all words. Finally, staff changes at PAN, the prime agency with carriage of the issue, resulted in the process virtually halting for several months.

During this pause a helicopter overflight was arranged, with one senior Traditional Owner present, to photograph sites from the air. These pictures were then used to show communities what the sites looked like. This operation was a great success and relationship building began. Time passed but progress was slow. It was not going to be possible to meet the deadline set by the lease. This system was not working and so a new process was required to be developed.

In 1999 a new approach began based on formalizing the consultation process by the creation of a committee. A meeting was held at a settlement that was the permanent home of the majority of the Gunlom Trust members. The idea was to discuss, in an informal atmosphere, how to get the process back on track. In particular to establish how the concerns and aspirations of the Traditional Owners could be addressed. After a slow start, the various parties discussed the size and scope of the issue. The main agreement at the meeting was that Traditional Owners would be the majority of the committee. Who else need to be represented in the consultative process was a topic that was discussed at length. The final agreed composition of the group was:

- Traditional Owners were selected by the community because they were custodians of sites and ceremonies within the affected areas and also some of them lived in the valley at times in the dry season. This group includes men and women from various communities and forms the majority;
- Parks Australia North (PAN) – A commonwealth entity being the lessees and so the agency has the responsibility to carry out the rehabilitation under the terms of their lease;
- Northern Land Council (NLC) – A statutory authority representing the interests of the Aboriginal community and providing them with specialist advice;
- Office of the Supervising Scientist (OSS) -A Commonwealth entity acting as technical adviser to PAN as well as having responsibility for uranium mining environmental affairs in the region;
- Northern Territory Department of Business, Industry and Resource Development (NTDBIRD)- The regulator of mining activity in the Northern Territory and thus has some statutory obligations.

This group named itself the Consultative Committee, a title that was most expressive of their primary function as it had no statutory power. This Consultative Committee then agreed to set a timetable for meetings and activities to try and ensure that the program would be completed following the deadlines set in the lease. The idea was that the technical experts could meet as often as they wished, but at agreed intervals progress reports would be presented to the whole group and decisions made as to the next step.

The communication plan system was agreed to be a major gathering every 6 to 8 weeks with any member of the Aboriginal communities concerned being welcome to attend. These meetings would hear presentations from the experts and then discuss the information. The style of the presentations was difficult to work out at first, but the great emphasis was put on the use of models, posters, pictures, diagrams and computer graphics. These techniques were very successful. For example, at times the use of small models has been the best way to demonstrate options for earthmoving. The choice of venue was also important as people need to be comfortable with their surroundings to relax and discuss issues. Thus, regular meeting rooms were not an option. Whilst having meetings in the open air at a shade house in the Ranger station or under trees at a campsite was fine in the dry season, once the wet season arrived meeting places had to be sheltered, cool and have facilities to provide food for participants.

A resort hotel and a motel were both used but they were far from perfect with many logistical issues and too many distractions. Whilst these options were used outdoor venues remained the first preference and proved to be most effective. In the dry season meetings were held in the country in the valley where sites could be easily visited if specific issues needed to be inspected or discussed. Having the whole group camping and eating together increased trust and mutual understanding.

At every meeting all outcomes, questions raised, and points agreed were written up on a flip chart. Each page was photographed as it was completed, and the photographs were compiled into a booklet and became the summary record of the meeting. This system made the community confident that records were truthful, and it enabled the memory of a decision to be seen in context.

The development of trust over time was apparent as gradually more cultural issues were raised by the community as they explained their concerns and aspirations. These included sacred site matters, gender-specific activities in parts of the valley, concerns with possible contamination of local food sources and wild fruits and animals, and so on. One element of the information transfer process was the organization of a radiological protection seminar for the Traditional Owners. Presented by an external, independent expert trainer, this explained what radioactivity is and how it relates to their everyday life. The outcome was a series of very discerning questions from the owners and a subsequent reduction in their concerns about radioactivity.

The planning process was extended due to the slow release of funds from the Commonwealth Government but over a few years, several studies were undertaken to provide data on flood levels, groundwater conditions and topography and geology. A comprehensive plan was developed to carry out work in two campaigns that would manage sites in order of safety priorities. At all stages of the process, the committee met at appropriate intervals to ensure the community was aware of progress at each stage.

Meetings were generally held in the country in the dry season two or three times over the season. During the wet season frequent, heavy rains limited activity and access to the valley and so there was little to report.

In 2005 funds for the final earthworks programme were released and the project went to tender. The chosen contractor was obliged to include traditional owners in the workforce both as cultural advisers as well as trainees on various equipment and tasks essential to the programme. The final containment site was located on a disused bush airstrip and the containment was built to a stringent specification to meet both chemical and radiological regulatory requirements. All the seven previous shallow containments were excavated progressively as the final containment was built. During the collection of materials, it was often noted that other deposits of tailings and waste became exposed, and these were also removed to the containment. The design had taken account of this possibility and extension of the long axis of the excavation was easily achieved as required. The major hazard during the works was construction traffic having to share roads with tourist traffic as the area became quite busy during holiday periods. Some sites were backfilled, roads were decommissioned, and sites were landscaped once decontaminated. Revegetation was all with natural species of local provenance. The overall programme was completed over two dray seasons and was very successful. Since completion in 2007, the containment site has remained fence and revegetation has been very successful. Monitoring of erosion for the cover and groundwater quality at the margins of the site continues to the present day (2020). It has been necessary to undertake some repairs to the cover following localized erosion issues, but these seem to have been resolved satisfactorily.

III.2. LESSONS LEARNED

- The major lesson learned was that above all, great patience is required when dealing with complex legacy site remediation. The lack of information and records commonly associated with legacy sites does not usually permit rapid progress in project development and planning;
- Communication with stakeholders is essential and must be clear, honest, and regular; also, it may need to be undertaken in a culturally appropriate manner. Care needs to be taken to correctly identify the appropriate stakeholders at the beginning of the planning process to maximize opportunities to develop trust and firm working relationships;
- Preparation of a comprehensive plan with clearly understood objectives and completion criteria is essential to the successful completion of the programme. Several studies may be required before the design stage to provide missing data necessary for design work to proceed;
- Designs have to meet regulatory requirements and have the approval of stakeholders, but ideally, also have the flexibility to be able to accommodate any unforeseen changes that may develop during the working phase of the project;
- Budgets needs to be realistic and include significant contingencies to compensate for the lack of detailed background information;

APPENDIX IV

REMEDIATION OF THE ARSENIC-RICH SLUDGE TAILINGS FROM A FORMER TUNGSTEN MILL (PORTUGAL)

IV.1. BACKGROUND AND OBJECTIVES

The present case study refers to a tailings' embankment facility known as 'Cabeço do Pião' (also named as *Rio tailing dam*) originated by the processing of tungsten ores in a former plant. The site is located near the currently active Panasqueira Mine close to the town of Covilhã, Central Portugal.

The Cabeço do Pião tailings impoundment belonged to the Industrial Complex of Panasqueira Mine (Fig. 11), which is one of the largest operating tungsten mines in the Market Economy Countries (MEC) [194]. At present, the Cabeço do Pião impoundment belongs to the municipality of Fundão.

FIG. 11. Panasqueira mine and Cabeço do Pião tailings deposit [194].

This mine started operating in 1896, focusing mainly on wolframite exploitation with cassiterite and chalcopyrite exploitation as by-products [195]. The main interest is a deposit of hydrothermal quartz–wolframite veins intruding into schists, known as Beira schists, and shales, where cassiterite and chalcopyrite ore minerals occur associated with arsenopyrite and pyrite.

One of the processing plants of this mine was located on the left bank of the Zêzere River where the ores were fully or partially processed between 1927 and 1996. The tailings were stored along the bank, in an extension of about 1.5 km. The fine particles, locally called 'sludge', were stored in a self-constructed embankment located on a steep hillside. In 1998, the plant and tailings disposal were deactivated, and all the operations were transferred to Barroca Grande with a more central location. Nevertheless, the long history of mining operations at the Cabeço do Pião site is attested by the presence of the tailings and other debris at the site, as well as old, abandoned infrastructures.

The estimated total volume of the deposited material is roughly 1,900,000 m^3, the slope of the hillside averages 36º, and the crest has an average height of approximately 90 m. The material drains directly to the Zêzere River (Fig. 12) which feeds three water dams. The last one, Castelo do Bode, located 90 km downstream, is one of the main water supply sources for Lisbon.

FIG. 12. Slope of the Cabeço do Pião tailings deposit.

Several minerals are present in the waste material, many of which occur in the form of sulphides, such as pyrite and arsenopyrite. The materials have been progressively oxidised to sulphate, naturally leaching some of the metals present. As a consequence, heavy metals such as cadmium, copper, tungsten, and zinc, are present with high concentrations but arsenic, in particular, with a very high concentration (about 15%) [196].

These materials, stored in the dam for more than fifty years, are a liability to the environment, the surrounding region, and the local population. The site became a threat because it was simply abandoned, and measures were not taken to reduce the risks to the environment. On the other hand, these tailings are also an attractive resource of critical and valuable metals with potential economic benefits. The interest in reprocessing the tailings coexists with the necessity to solve the environmental problems.

This tailings storage was not included in the National Plan for Rehabilitation of Abandoned Mines, despite presenting a high environmental risk. The site belongs to the municipality of Fundão, which has full responsibility for the remediation/rehabilitation of the site and further monitoring. The need for remediation has also been lately driven by the population demand to bring the site back into use, proving the safety of the place. The late accidents in other countries with active tailings dam failures brought new concerns about the site.

The purpose of presenting this case study is to illustrate the gap in the application of decision-making tools in what concerns remediation strategies for this site. The Cabeço do Pião site can be used as an example to explore the application of different methodologies in decision-making to select the most suitable technology for the remediation project. And, although not referring to a radioactively contaminated site, the environmental issues are common to many contaminated sites, such as the presence of heavy metals, the generation of acid mine drainage, slopes instability, and economic and social constraints.

IV.2. THE TRANSFER OF THE SITE RESPONSIBILITY

In 1993, due to several years of low wolfram prices, the mining company (Minorco) presented a request to the General Directorate of Mines to close the mine. As the permission could only take place after the establishment of the mine closure conditions, Minorco decided to sell the company to Avocet Mining.

During the initial period of Avocet (1993-2004) many changes took place, namely the reopening of the Mine in January 1994 and the transfer of the Plant from Rio to Barroca Grande (Fig. 13) [197].

But the final period of Avocet management was of significant economic difficulty due to the extremely low and persistent wolfram prices. The deterioration of the production capacity of the mine led the Company to notify the General Directorate of Mines of its intention to close the mine from January 2004.

FIG. 13. Barroca Grande tailings and the São Francisco de Assis Village.

Following negotiations and based on well-founded expectations that within six months there would be an increase in prices, the State guaranteed the payment of the workers' salaries between March and August 2004 through the Wage Guarantee Fund, which created conditions for the recovery and acquisition of the mine by Almonty.

From May 2004 to October 2007 the American group Almonty managed the mines. During this period the productive capacity of the mines was restored.

The Japanese company Sojitz Corporation acquired the Panasqueira Mines in October 2007 and sold it back to Almonty in January 2016. During this period the company changed its name to Sojitz Beralt Tin and Wolfram Portugal. Exploration was carried out in a very extensive area of the mine. Exploration of tailings that contained interesting wolfram grades was done in the old plant of the Village of the Panasqueira.

In 2008, part of the concession that was located south of the Zêzere River was released (where it was included the Cabeço do Pião site). Management of the old infrastructures become the responsibility of the municipality of Fundão. The site was 'given' to the municipality to build infrastructures related to thematic tourism (industrial archaeology) and sports adventure. The mining company is still responsible for the monitoring of the water of the Zêzere River.

Almonty Industries is the current owner of Panasqueira mine, having acquired the mine on 06/01/2016, and once again changing the name to Beralt Tin and Wolfram. The possibility of recovering several metals contained in the slime's dams, especially wolfram, tin and copper, is being studied at the moment.

IV.3. EXPECTATIONS AND OPPORTUNITIES FOR THE SITE

The site is within the countryside, surrounded by several villages dispersed through the mountains. At the top of the site, 29 inhabitants have been living ever since. Most of them are descendants of former miners and workers of mining companies. The inhabited houses that resist do not have basic sanitation or water from the public network; the water supply comes from a pump that transports it through visibly degraded pipes and directly grounded, and that freezes with winter frosts. Public transport is scarce, the baker passes three times a week, and the commercial spaces are inexistent. There are global discontentment and discouragement from the local population caused by failed promises on expectations and opportunities in transforming the village and the site into a tourism complex.

In general, the population is not aware of the physical and chemical risks of the site. The community regards the existing mining company as essential for the local economic subsistence, where the economic and social benefits overlap with environmental degradation.

The Fundão municipality, following the management of the mining complex and subsequent planning of the revitalisation and tourism promotion of the region, projected, in addition to the hotel unit, a whole set of facilities that included a mining museum, a space for recreation, delimitation and signalling of routes. But the only work completed and in operation is the *Casas da Mina* hostel inaugurated in 2007. Everything else expects better days because the millions invested at the time were not enough to soften the impact of the legacy left to abandonment.

The site is not fenced or even signalised, and there are no warnings for physical and chemical risks. People are invited to cross the tailings at the bottom of the impoundment where there is a walking trail, integrated into the Great Route of the Zêzere, for 370 km along the Zêzere River and through 13 districts. The entire route is walkable but without safety in what concerns to the part that crosses the site.

Foreign visitors are staying at the hotel unit, some for spiritual retreats, and some for the treatment of skin problems (e.g., eczema) with the river water, which receives the runoff waters from the impoundment with high arsenic concentrations.

This site has been the target of many environmental studies and research funded projects over the years [198,199]. The conclusions have been the same in what concerns the geotechnical stability and heavy metals content, in particular the concerns arising from the high arsenic concentration and lately the use of the site by the local population and foreigners as well. Unfortunately, none of them conducted to the implementation of a remediation project for the site, despite the available detailed data from the site characterisation and studies assessing the exposure and risk developed specifically for the municipality of Fundão.

IV.4. THE LEGAL FRAMEWORK

The Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability about the prevention and remedying of environmental damage (ELD) establishes a framework based on the polluter pays principle to prevent and remedy environmental damage [200].

The ELD was amended four times through on the management of waste from extractive industries, through Directive 2009/31/EC on the geological storage of carbon dioxide and amending several directives, through Directive 2013/30/EU on the safety of offshore oil and gas operations and amending Directive 2004/35/EC, and through Regulation (EU) 2019/1010 on the alignment of reporting obligations in the field of legislation related to the environment. The amendments broadened the scope of strict liability by adding the ‘management of extractive waste’ and the operation of storage sites according to Directive 2009/31/EC to the list of dangerous occupational activities in the ELD [200].

The Multi-Annual Work Programme (MAWP) 'Making the Environmental Liability Directive more fit for purpose' has been developed in response to the REFIT [11]evaluation which showed clear knowledge gaps and implementation deficiencies that need to be tackled in a more structured and systematic way [200].

The MAWP was finalised in a consultative process with ELD government experts from the EU Member States. The current version of the MAWP was endorsed by the government experts at the 17th ELD government experts meeting on 28 February 2017. The MAWP 2017-2020 is updated annually to changing developments, growing knowledge and new requirements [200].

The present MAWP consists of three main pillars [200]:

- Improving the evidence base for evaluation and decision-making for the Commission, Member States, stakeholders and practitioners (assessment framework and ELD registry);
- Supporting the implementation through tools and measures for more even implementation (common understanding of terms and concepts, capacity building and training);
- Ensuring sufficient availability of financial security, in particular for large losses or in case of insolvency (secure, adequate and available instruments to cover ELD liabilities).

The last inventory of the Portuguese closed mine facilities was published in 2013. According to the inventory, the tailings of this site do not exist in an abandoned mine. It was considered that the tailings are already safely contained and therefore do not originate leachates, acid drainage and dust that could affect the normal usage of the soil, having only some safety problems (it is presumed related to the stability of the side-hill impoundment).

On the other hand, if the tailings are considered as wastes, according to the European Legislation, the sludge is deemed to be carcinogenic with the Hazard Class HP7 (Regulation (UE) Nº 1357/2014). Several toxicological effects have to be taken into consideration: acute toxicity 3 (inhalation) (H331), acute toxicity 3 (oral) (H301), aquatic acute toxicity 1 (H400), and chronic aquatic toxicity 1 (H410).

If the tailings are considered as contaminated soil, then the Environmental Protection Act of the Ontario State (Canada) applies and therefore the concentration of several elements are above the allowable values (e.g., Sb, As, Cu and Zn).

Although there is a well-established legal framework_on environmental liability concerning the **prevention** and **remedying** of environmental damage (ELD) based on the **polluter pays principle**, and in which this case study fits in, the municipality does not have by itself the financial conditions to secure and perform the remediation of the site.

[11]A rolling programme to keep the entire stock of EU legislation under review and ensure that it is 'fit for purpose'; that regulatory burdens are minimised and that all simplification options are identified and applied.

IV.5. THE LIABILITY TO THE ENVIRONMENT AND THE POPULATION

Two types of mining wastes are stored at the site. The coarse tailings contain low levels of heavy metals and sulphides, with a reduced potential of environmental negative impact. And fine tailings (the 'sludge') with high levels of heavy metals and sulphides, with very high potential for negative environmental impact [196].

The storage area was originated by auto-construction, taking advantage of the topography of the site, and using the coarse wastes to create the supporting wall of the embankment [201]. There are still relatively high concentrations in Zn (1.41%), Cu (0.60%) and W (0.39%).

The stored volume of 'sludge' is approximately 730 000 m^3; the total volume of the storage area, including supporting walls is approximately 1 200 000 m^3 and the total volume of material to smooth the shape (mostly sandy material) is approximately 2 630 000 m^3. This means that 61% of the material existing in the storage area is constituted by fine tailings, while the remaining 39% was used to build the support wall and for smoothing the topography [196]. The impoundment occupies a total area of approximately 2000 hectares.

The deposited material has acidic pH ranging from 1.4 to 3.6. The pH at the surface is lower due to the oxidation of the existing sulphide minerals. Heavy metals and metalloids are present in the waste material: As, Cu, Fe, Hg, Mn, Sb, Sn, W and Zn and several minerals were also identified such as quartz, mica, feldspar, illite-vermiculite, arsenopyrite, marcasite, pyrite, pyrrhotite and chalcopyrite. Some other minerals, such as scorodite and natrojarosite, resulting from the oxidation of arsenopyrite, are also present in smaller quantities and enriched in As, Cu, Mn, Pb and Zn.

Arsenopyrite is stable under reducing conditions, however, like other sulphide minerals, it is oxidised by weathering effects when in contact with water and oxygen yielding sulfuric acid (acid rock drainage - ARD). This acid can solubilise the solid mineral constituents, produces a solution containing acid and dissolved metals. Specifically, the ARD of arsenopyrite releases arsenide and arsenate species, which requires special treatment during the oxidation process due to its toxicity [196].

The concentrations of metals in the leachates, which percolate from the tailings directly to the Zêzere river, are quite variable, spatially and seasonally. For example, for the arsenic concentration, values between 6 300 $\mu g\ l^{-1}$ and 99 000 $\mu g\ l^{-1}$ were registered in March and June 2018 sampling events, respectively, at samples, collected at the base of the slope. The pH of the leachates was around 3.

Arsenic is toxic and carcinogenic by all exposure pathways (except inhalation) and is continuously released from the tailings' embankment to the environment through the leachates produced inside the storage and released on the slope of the hillside, and by wind action since the storage has no cover. From a carcinogenic perspective, the risks obtained for any of the three routes of exposure, including inhalation, show that the population is exposed to a much higher carcinogenic risk than the acceptable values.

In what concerns the structural stability and the risk of the tailings dam failure there is a continuous erosive action originating the removal and mobility of material. There is a resurgence of water at the top of the embankment's slope which may be responsible for the erosive process visible in the slope [196]. The failure by the erosion of the containment wall of the embankment (Fig. 14) is the most probable type of failure to occur and will lead to a partial collapse of the dyke retaining wall, which will fall into the valley [196].

FIG. 14. Most probable area of failure by erosion of the embankment wall and erosion zones below the support wall.

It is estimated that, in case of such failure occur it will release 200,000 m^3 of waste, equivalent to 490 600 metric tons, with a total arsenic content of 73 590 metric tons. Simultaneously, about 91 400 m^3 of leachates would be released with an average concentration of 6 300 g/L corresponding to a release of 575.8 kg of dissolved arsenic [196].

The runoff waters from the tailings embankment present high acidic pH's (~ 3) and high concentrations in Al (99 - 161 mg/L), As (146 - 2140 g/L), Cd (226 - 464 g/L), Cu (20 - 54 mg/L), Mn (22 - 93 mg/L) and Zn (22 - 49 mg/L). They also show high concentrations in suspended solids [196].

The concentrations of As in the runoff waters are frequently over 2000 g/L while it is much lower in the river background (4 g/L). In the river, the As is sorbed by the iron oxides and hydroxides, precipitating at the bottom of the river and integrating the sediments which present high concentrations in As (333-1489 mg/kg) [196].

There is no indication of groundwater contamination due to the Cabeço do Pião embankment. However, the concentrations of heavy and metalloid metals (As, Cd, Cu and Mn) in potatoes and cabbage leaves, locally produced, showed that the concentration of As could range from 0.8 to 14.4 mg/kg. The limit established by FAO/WHO is 0.1 mg/kg [196].

IV.6. THE REMEDIATION/REHABILITATION ALTERNATIVES FOR THE SITE

The decision for remediation of the Cabeço does Pião embankment has not been taken yet. Since the site has a legal owner, the payment from the polluter applies. The situation remains the same over the years due to the lack of financial resources from the Fundão municipality.

The interest in reprocessing the tailings coexists with the necessity of remedying the environmental damage at this site. Re-mining and reprocessing could be a way of income to support part of the necessary funds to rehabilitate the site. On the other hand, the current remediation alternatives being considered for the site imply great physical works in a challenging topography (e.g., relocation of the tailings, geo-chemical stabilisation of tailings and covering, demolition of structures, treatment of contaminated water and site rehabilitation). The monitoring of the site for chemical and physical stability will have to be assured too.

From the technical point of view, several alternatives have already been considered for the Cabeço do Pião tailings deposit [194]:

- Re-mining with reprocessing. Advantages - high grades in W, Cu and Zn. Disadvantages - low tonnage; high capital costs; and foreseen high processing costs. Uncertainties - there is no guarantee of solving the arsenic issue, but a new sealed storage facility would be needed for arsenic;
- Cover on-site of the tailings. Advantages - avoids leaching and especially weathering with the incorporation of arsenic in the sediments. Disadvantages - topographical issues implying a complete reshape of the disposal; movement of a large volume of material in difficult topography. Uncertainties - several solutions are possible: complete cover on-site; transportation of tailings and covered storage in another location;
- Excavation of the tailings, transport to another location followed by confinement. Advantages - sealing off the tailings becomes possible. Disadvantages - a large volume of materials need to be transported; reshape of the actual facility after the removal of the tailings. Uncertainties - choice of the new area in the vicinities and the necessity of an impervious bottom;
- Excavation of the tailings followed by immobilization at another location. Advantages – immobilization of the tailings. Disadvantages - a large volume of materials need to be transported; choice of the new location; the cost of the process. Uncertainties - several solutions are possible: cementation; solidification; polymeric resins;
- In-situ immobilization. Advantages - avoid transport and human contact. Disadvantages - the environmental setting maybe not be adequate (e.g., not enough porosity). Uncertainties - several solutions are possible: cement, clays, polymeric resins, and geochemical immobilisation.

The high costs of ongoing conventional treatment, total removal, and/or management combined with the scale of potential health and environmental risks make it important to evaluate different remedial alternatives.

IV.7 EVALUATION OF THE REMEDIATION TECHNOLOGIES

Several elements necessary for a decision-making process were developed and put together for the ReMine project. Following a simplified six-step decision protocol[12] the critical elements to be considered are: 1) review of existing site data, 2) identification of absolute objectives, 3) identification of functional objectives and metrics, 4) identification of potential technologies as a function of the site and contaminant characteristics, 5) selection of appropriate technology and 6) design and implementation of the chosen technology [202]

The collection of site-specific data feeds each step of the process and is used to refine the site conceptual model. The process involves the iterative characterisation of the contaminated site, development of remediation objectives, and evaluation of technologies [202].

The development of remedial objectives for the site is inherently a social valuation process, to which stakeholders will bring different (and perhaps irreconcilable) points of view. The process requires differentiation between absolute objectives (which are not substitutable) and functional objectives

[12] A protocol is defined as a strategy and methodology to be followed for accomplishing a stated purpose—in this case, the remediation (through removal, transformation, or isolation) of the source material.

(substitutable alternatives to meeting those absolute objectives). Making this distinction demands careful communication with stakeholders, in particular, where a particular objective, such as attaining minimum contaminant levels at a particular point in time and space, may be a functional objective for one stakeholder but an absolute objective for another stakeholder [202].

The involvement of the stakeholders is an important contributor to the decision-making process. Nevertheless, in this particular case study, misunderstanding and prejudice related to both the existing and the new potential mining projects in the region, have disrupted the trust between the local population and the municipality. So far, the identified potential technologies for the site remediation (using the protocol, it was possible to move up to step No 4) were not discussed with all stakeholders, in particular, the public.

The following generic absolute objectives may be defined: i) reduce the contaminants concentration levels to which the population is exposed; ii) eliminate the acid generation at the site; ii) preventing damage to identified environmental receptors; iv) long-term geotechnical stability of slopes and surfaces; v) upper sealing with reshaping of the site and vi) protect human health.

Accordingly, the functional objectives may be established: i) preventing migration of contaminants off-site; ii) mass removal from the source; iii) concentration reduction at the site; iv) mass flux reduction; v) reduction of the toxicity of the general site; vi) life cycle costs minimization; and vii) acceptance of the remedial option by the community.

Some metrics may be given by i) mass of contaminated material removed; ii) residual metals concentrations and, iii) contaminants released from the site.

The mass of contaminated material removed is the mass of contaminated material that needs to be removed is dependent on the solution chosen for rehabilitation and it varies between a minimum of 2676000 and a maximum of 5900000 metric tons;

Residual metals concentrations are based on the chemical analysis of the 80 samples that were collected during the REMinE project, the elemental composition of the tailings is shown in the next table. Other elements that did not have significant concentrations were analysed, being below or near the detection threshold (Ga, Ge, Mo, Ag, In, Au and Pb).

TABLE 11. ELEMENTAL COMPOSITION OF THE TAILINGS FROM CABEÇO DO PIÃO IMPOUNDMENT

	Concentrations (%)								
	Mn	Fe	Cu	Zn	As	Sn	Sb	W	Hg
Average	0.15	27.8	0.60	1.41	15.5	0.09	0.01	0.39	0.05
Stand. Dev.	0.080	1.75	0.20	0.38	2.98	0.02	0.001	0.13	0.008
Median	0.15	27.4	0.55	1.43	14.9	0.09	0.01	0.40	0.05
Max.	0.27	31.3	1.15	2.78	22.2	0.12	0.01	0.59	0.07
Min.	0.01	24.3	0.20	0.72	10.2	0.06	0.00	0.06	0.03

The coarse tailings ('sands') that were deposited in the steeply left bank of the river, between the mill and the sludge embankment, show much lower concentrations in toxic elements: As - 0.55%, Cu - 0.03%, Zn - 0.02% and W - 0.06% and they can remain at the site.

Regarding the third metric, i.e., contaminants released from the site, the main mechanism of release is the transportation of leachates stored inside the embankment. They are released in the slope, below the wall of the dyke, and move downwards to the riverbank. The composition in dissolved arsenic of these leachates is highly variable, depending on the season – from 561 up to 99000 $\mu g\ L^{-1}$. A value of 6300 $\mu g\ L^{-1}$can be considered as an annual average. Leachates also evidence high concentration in cadmium (weighted average 440 $\mu g\ L^{-1}$) and copper (weighted average 40 $\mu g\ L^{-1}$). A significant fraction of arsenic is sorbed by the sands, with high iron content, existing at the bottom near the river. On an annual average, the river receives 92.7 m^3/d of leachates with an average concentration of 2140 $\mu g\ L^{-1}$. Taking into consideration their releases from the actual mine and the background concentration, it was estimated that the river, from that point downwards, has an average flow of 19 m^3/s with an average concentration in As of 5.1 $\mu g\ L^{-1}$ [196].

The potential technologies were already identified, as mentioned in the previous section. The likely efficacy of a given technology is dependent on the contaminant type, the environmental setting at the site (e.g., is the porosity of the material suitable to apply in-situ immobilization?) and the chosen functional objectives [202].

The potential for success of each one of the identified technologies can be rated as *high, medium, low or unknown*, relative to the specific functional objectives. The next step is to decide about which remedy to pursue (assuming that more than one possibility was identified). One approach to reach a decision systematically is by constructing a matrix of objectives *vs.* candidate technologies.

Technologies that were identified are listed in the vertical column, and functional objectives are listed across the top of the matrix. Each intersection represents the ability of a particular technology to meet a particular objective. All of the entries in a given row need to be considered to give a total rating for each technology (in this case, qualitative and narrative ratings were used rather than numerical scores).

The development of matrices for alternative remedial options have to involve all stakeholders and it needs to be well documented. Stakeholder participation is needed to better understand the range of absolute objectives at a given site, to develop functional objectives, and to gain consensus on appropriate actions. Without adequate public participation, critical elements of solutions may be missed, part of the involved parties may feel that their needs have been ignored, and/or false expectations may develop as to what can be achieved [202]. This seems to be the case for this particular site.

Once all stakeholders agree to the evaluation, one or two selected technologies will then be carried further through a highly detailed feasibility analysis. The design and implementation of chosen remediation technologies follow standard engineering practices.

IV.8 DECISION ON THE EVALUATION OF THE REPROCESSING ALTERNATIVE

Under the ReMine project, a preliminary proposal for the optimization of the tailing reprocessing from the 'Cabeço do Pião' embankment was developed. The model consists of a multi-objective criteria optimisation using genetic algorithms (GA) to decide on the feasibility of reprocessing [203].

The strategy is mostly focused on re-mining and reprocessing, taking into account the technical, economic (planning, operation and decommissioning), social (development, engagement, employment), and environmental (characterization, rehabilitation, remediation, control and monitoring) aspects. It is assumed that this strategy would solve the environmental issues of the site.

The multi-objective solution to optimization problems by GA consists in matching each problem into a scalar fitness function. In this case, every single objective is evaluated and so it is attributed a weight according to its quality [204]. The expected solution will be around in the high-performance of the multi-objective functions.

For the present case study, the initial population is given by the circuit configurations, characterized by scores such as the metal recovery, the characteristics of the new tailings generated and the social and economic features. The objectives functions were stated as: i) maximization of the metal recovery; ii) minimization of the operational cost; iii) minimization of the environmental and social risks [205].

The impacted population will need to be minimized, as well as the impacts generated. The reduction of the volume and the increase in the stability of the neo-tailings storage contribute to the minimization of the risks. The relative importance of each recoverable metal will depend on the quotation in the market.

First, the technical aspects of tailings reprocessing were covered by a multi-objective parametric optimization (W and Zn grades and recoveries) based on mathematical models and processing laboratory results. Then, economic, environmental and social constraints were added to the different technical configurations included in the multi-objective structural optimization process. The conceptual cost analysis included the closure of the re-mining project: transport of neo-tailings, encapsulation with geo-polymers, care and maintenance and monitoring for at least 5 years [205].

Technically, the re-mining project is feasible: studies of recovering copper from tailings reached over 86% efficiency and for cassiterite approximately 70%. The recovery of tungsten by pressure leaching using NaOH reached an average of 80%. A parallel asset from the reprocessing alternative is the potential improvement of the life quality of the local community in terms of environmental, social, and economic outcomes.

Given the economic relevance on the commodities market (W as a rare strategical metal and critical raw material, Zn as the third most consumed metal in the world), the re-mining and reprocessing project may be a viable solution for the lack of funds for the remediation of this site [203]. Nevertheless, there is a strong drawback in this re-processing solution: the relatively small amount of this secondary raw material is not enough to pay back the required investments. An ultimate solution can only be found considering simultaneously the tailings of the present processing plant that exist in a much higher quantity.

IV.9. LESSONS LEARNED

Preparing an adequately and justified remediation strategy need to take into many technical and non-technical factors. The effectiveness of the remediation options and the cost and resources required for their implementation can vary considerably depending on these factors. Therefore, generalised recommendations that do not take into account the diversity of local site-specific conditions can result in inadequate decision-making and may not be feasible to implement [206].

Some of the factors influencing the remediation decision-making process can be challenging to implement in practice because some of them will lay on subjective decisions. One example is that assigning the relative importance of different technical and non-technical factors, which will determine the effectiveness and efficiency of the remediation options, needs the incorporation of expert judgements [206]. In this context, decision aiding methods are useful tools to support decision-making on how to implement remediation in contaminated areas requiring individuals and society to make decisions that acknowledge the trade-offs between the various factors and constraints involved in the process: the diverse environmental, social, economic, and health consequences of personal, corporate, or societal actions [207]. This is only achievable if all relevant management options are identified and there is information available on each of them outlining the factors and constraints involved in their implementation and quantifying their effectiveness.

Several challenges are yet to be overcome at this site and for sure will need improvement:

- A comparative and comprehensive analysis in what concerns both approaches: re-processing the tailings (which has implicit the remediation of the site) or remediate the site (without re-mining);
- It is worth applying multi-criteria decision analysis to support decisions in this rehabilitation project, including technical and non-technical factors (e.g., the accentuated topography may be a limiting factor for many of the considered solutions for the site);
- Built trust relations between the community and the municipality and the existing mining company (there is a general fear in what concerns the existing mining company as a local job provider). A very well accepted and good relationship was established during three years with the Academia under the REMinE project. During this period, it was possible to get the perception of the discontentment of the community. Strangely, there is a complete lack of perception in what concerns the physical, chemical and toxicological risks to which the community is exposed;
- Engagement of all stakeholders involved in the decision-making process - there has been no discussion so far;
- The optimization of remediation measures for complex sites is often a multifaceted and demanding task within the decision-making process. Under the MAESTRI a framework is developed that may be applied for this site to support the evaluation of measures.

APPENDIX V

REMEDIATION OF LARGE CONTAMINATED OFF-SITE AREAS FOLLOWING THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT (JAPAN)

V.1. INTRODUCTION

On 11 March 2011, the accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) released large amounts of radioactive materials, mainly radioactive cesium and iodine, into the atmosphere and contaminated the land in Fukushima and neighbouring prefectures (Fig. 15). Because of concerns about the possibility of a large-scale release of radioactive materials, and health risks, a Restricted Area (the area within a 20-km radius of the F1NPP) and Deliberate Evacuation Areas (heavily contaminated areas outside of this zone) were designated. In the days and weeks following the accident, approximately 85,000 people from 11 municipalities were evacuated from these areas, which cover approximately 1170 km2 (Fukushima Nuclear Accident Independent Investigation Commission [208]. In response to this unprecedented large-scale contamination of national land, the Japanese government decided to implement a decontamination project on a scale previously unseen anywhere in the world.

In the following, the decontamination project implemented in the off-site areas following the F1NPP accident is outlined and explained, the challenges encountered in the project, the consequences of the project, and recommendations resulting from the project. Decontamination of some areas and disposal of wastes generated by decontamination is still ongoing; this report is based on information collected as of May 2021.

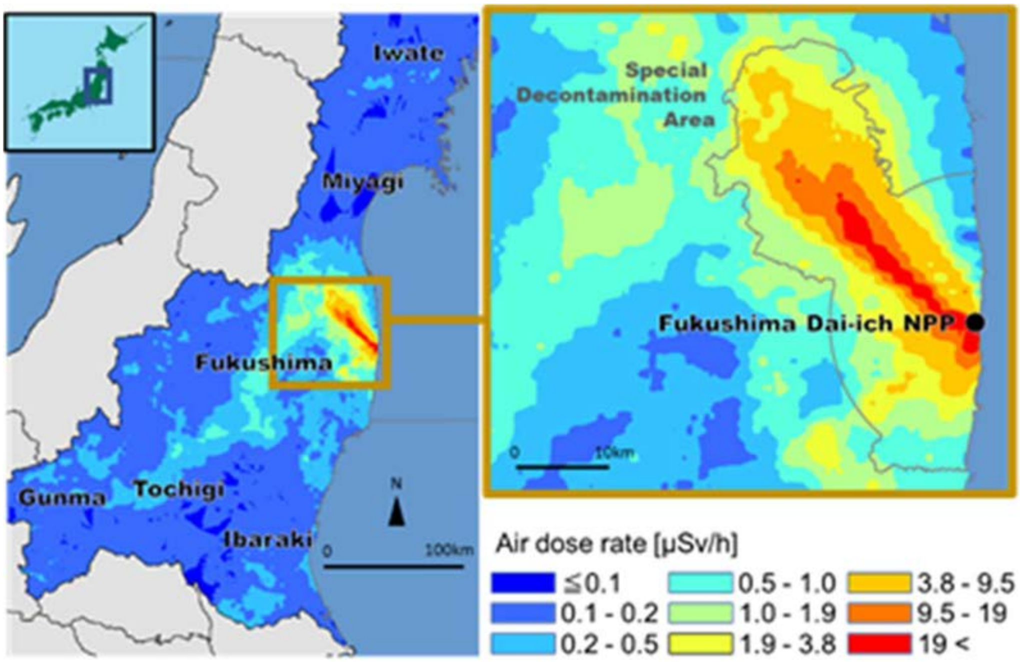

FIG. 15. Ambient dose rates are determined by airborne monitoring units. Source: Measurements from the 5th aircraft monitoring by MEXT (28 June 2012).

V.2. DECONTAMINATION PROJECT IMPLEMENTED OFF-SITE AREAS FOLLOWING THE F1NPP ACCIDENT

As it became clear that radioactive contamination was spreading across Fukushima and neighbouring prefectures, it became necessary to take immediate action against radioactive materials in the affected areas. Although the Act on Special Measures Concerning Nuclear Emergency Preparedness (Act No. 156 of 1999) stipulates the emergency response measures after a nuclear disaster, and international organizations such as the International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP) had issued recommendations and standards for how to deal with environmental contamination and how to prevent public exposure at the time of an accident, the practical framework for dealing with the contamination caused by radioactive materials released into the general environment was not fully in place in Japan [209]. Immediately after the accident, Fukushima Prefecture, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and other related organizations began monitoring outdoor radiation levels to understand the radiological conditions in the affected areas. In the vicinity of F1NPP, radiation levels were monitored using monitoring vehicles. In addition, MEXT started airborne monitoring approximately two weeks after the accident and started wide-area airborne monitoring within an 80-km radius in April 2011. Soil, food, tap water and other potential sources of human exposure were also monitored for contamination.

V.2.1 Emergency Response Periods: March-August 2011

Based on the monitoring results, it was decided to prioritize the implementation of measures to protect children against radioactive contamination. Concerning the use of schools, MEXT announced on 19 April 2011 the Tentative Approach to Determining the Use of School Buildings, Schoolyards, etc. in Fukushima Prefecture, and decided to restrict outdoor activities inside and outside school buildings with measured ambient dose rates of 3.8 μSv/h or higher in schoolyards and gardens. Subsequently, on 26 August, MEXT released Reduction of Radiation Doses at School Buildings and Schoolyards in Fukushima Prefecture, in which it was decided in principle that the radiation dose received by children and students at schools would be 1 mSv or less per year and that the air dose rate in schoolyards and gardens would be less than 1 μSv/h, taking into consideration the behavioural patterns of children and students. The ICRP recommendation for the reference level was 1–20 mSv, but 1 mSv, the lowest value, was set as the target considering the importance of continued efforts to lower radiation doses at schools where students spend most of their time [210].

Based on the MEXT guidelines for the use of school buildings and grounds, Date City conducted a decontamination demonstration starting on 21 April 2011 at a schoolyard, and Koriyama City began removing topsoil from schoolyards on 27 April 2011. Although there were several decontamination options, the removal of the topsoil was done first as an experimental demonstration, because it was a voluntary effort using the readily available tools. In May 2011, the Japan Atomic Energy Agency (JAEA) started a field survey to verify measures for reducing the ambient dose in schoolyards and playgrounds.

During this period, several municipalities, including Date City, Minamisoma City, and Iitate Village, started decontamination activities, using experts with knowledge of radiation acting as decontamination advisors. These efforts mainly consisted of decontamination activities for local facilities such as schools and specific houses, and people began to recognize that areal decontamination was necessary to achieve a sufficient reduction in radiation dose. Voluntary decontamination activities were also implemented in various locations during several months after the F1NPP accident.

V.2.2. Establishment of a legal framework and decontamination policy: Decontamination Preparation Periods: August -December 2011

The Japanese government passed The Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District off the Pacific Ocean Earthquake that Occurred on 11 March 2011 (hereinafter referred to as the 'Act on Special Measures') and established a roadmap for effectively addressing and implementing the decontamination process. The Act on Special Measures was promulgated on 30 August 2011 and was fully enforced beginning on 1 January 2012. The Act on Special Measures clearly defines the responsibilities of the national and local governments and Tokyo Electric Power Company (TEPCO). Under the act, a framework and guidelines for decontamination operations were released, Decontamination Guidelines (December 2011) [211], which covered methods for surveying and measuring the degree of environmental contamination in intensely contaminated areas, as well as measures for decontamination, and guidelines for collection, transport, and storage of removed soil. On 29 October 2011, the MOE released the Basic Policy on Interim Storage and Other Facilities Required for the Handling of the Environmental Pollution from Radioactive Materials Associated with the Accident at the TEPCO Fukushima Daiichi Nuclear Power Station, which stipulated certain policies, such as having one interim storage facility in Fukushima Prefecture for soil and waste from Fukushima Prefecture and having final disposal outside Fukushima Prefecture within 30 years after beginning interim storage.

Moreover, under the Act on Special Measures, the contaminated areas were separated into two categories. The first is the Special Decontamination Area (SDA), which overlaps with the area under evacuation orders, where decontamination is implemented directly by the national government. The second is the Intensive Contamination Survey Area (ICSA), which is overseen mainly by local municipalities and encompasses all other areas. Eleven cities, towns, and villages (of which four are partial areas) were designated as the SDA and 104 cities, towns, and villages were designated as the ICSA (of which four cities, towns, and villages overlap the SDA). The population of the 11 cities, towns, and villages in the SDA before the evacuations was approximately 80,000 in an area of about 1150 km2. The total area subject to decontamination including both the SDA and ICSA was about 25 000 km2 with a resident population of about 7 million [211].

V.2.3. Implementation of Decontamination Project

In the SDA the MOE formulated a decontamination plan and carried out decontamination, whereas in the ICSA the MOE designated areas that required intensive investigation of the environmental contamination. The decision on whether to implement decontamination in the ICSA was left to the individual municipalities, which carried out the investigations and determined the area for decontamination and the implementation plan based on the results (Fig. 16).

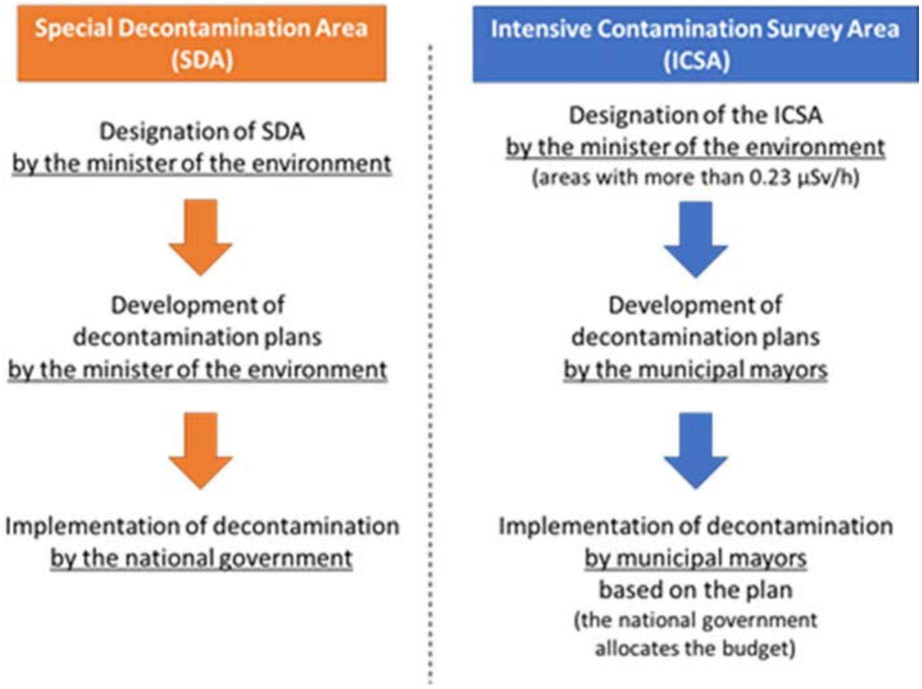

Fig.16. The flow of decontamination in the SDA and ICSA.

The SDA and ICSA had different entities overseeing the decontamination, but the steps in the required process were the same (Fig. 17).

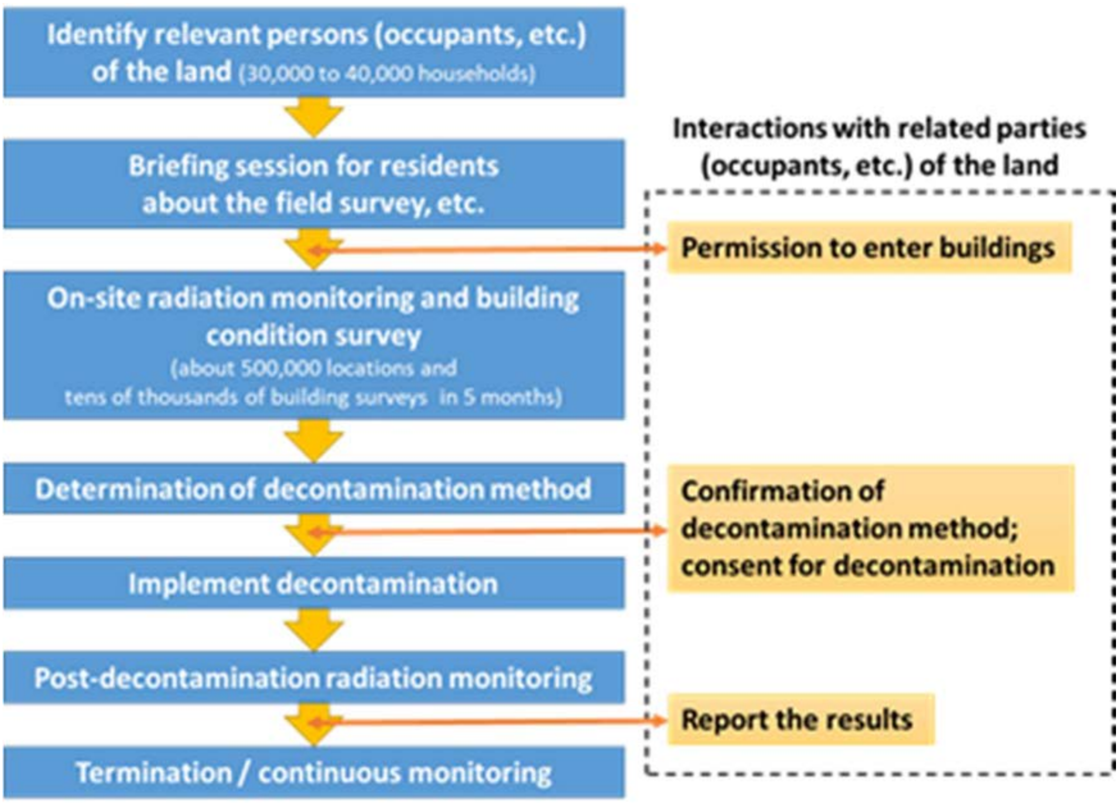

Fig. 17. The SDA and ICSA entities for overseeing the decontamination.

There are seven general steps for implementing decontamination work in the affected areas (Table 12). After briefing the residents, the owners of the land and buildings to be decontaminated were identified, preliminary radiation monitoring was started, and the condition of the house or building was determined. From the results, decontamination plans were prepared for each parcel of land and building, the decontamination methods were confirmed with the owners, their consent for decontamination was obtained, and the decontamination work was carried out. After the decontamination was completed, the effects of the decontamination were confirmed through post-process radiation monitoring, and the results were reported to the owners of the land and buildings.

The MOE formulated a decontamination plan to be implemented under the direct supervision of the government and announced a Policy for Decontamination in Special Decontamination Areas [212]. This planning policy specified a series of steps consisting of the model demonstration project, preliminary decontamination and whole-area decontamination, and processes for each of the Areas under Evacuation Orders. Furthermore, it seemed that the goal for lifting the evacuation orders is the return of the residents and the rebuilding of their lives, so the development of social infrastructure and the restoration of municipal office functions were advanced along with the decontamination work.

TABLE 12. STEPS FOR IMPLEMENTING DECONTAMINATION IN THE AFFECTED AREAS

No	Step	Description
1	Brief residents	Held a briefing session for residents in each district to explain radiation and the decontamination plan, method, and period.
2	Obtain consent for decontamination	Explained the scope of decontamination and detailed conditions for implementation to the owners and obtained their consent.
3	Secure temporary storage space	Secured temporary storage site with the cooperation of residents, the head of the administrative district and the head of the neighbourhood association.
4	Monitor radioactivity before decontamination	Measured radiation levels in the target areas before decontamination
5	Implement decontamination	Implemented decontamination
6	Monitor radioactivity after decontamination	Measured radiation levels in the target areas after decontamination
7	Follow-up monitoring	Conducted post-decontamination monitoring for approximately 6 months to 1 year after completion of decontamination

In April 2012, considering the Decontamination Roadmap, the Ministry cooperated with Tamura City, Naraha Town, Kawauchi Village, and Minamisoma City to draw up decontamination plans, and in July whole-area decontamination commenced in Tamura City, Naraha Town, and Kawauchi Village. Decontamination plans were gradually drawn up for other municipalities in the SDA, and whole-area decontamination began there as well. Among the areas specified for decontamination in the plan, decontamination in the SDA was completed in Tamura City, Naraha Town, Kawauchi Village, and Okuma Town by March 2014, in Katsurao Village and Kawamata Town by December 2015, in Futaba Town by March 2016, in Iitate Village by December 2016, in Tomioka Town by January 2017, and in Namie Town and Minamisoma City at the end of March 2017. That is, by the end of March 2017 decontamination was completed in all 11 municipalities in the SDA.

Based on the Act on Special Measures, 104 municipalities (population, approx. 6.9 million; area, approx. 24,000 km^2) in 8 prefectures including Fukushima Prefecture were designated as the ICSA. Fukushima Prefecture prepared Technical Guidelines for Decontamination Operations on 31 January 2012 and the Handbook for Whole Area Decontamination on 29 March 2012, so that when municipalities implemented decontamination they could collaborate regionally, and act based on regionwide and unified information.

In the ICSA, according to the procedure specified in the Act on Special Measures, the MOE designated areas where the additional annual exposure (i.e., in addition to background radiation exposure) was expected to exceed 1 mSv (or 0.23 µSv/h, assuming 16 h indoors and 8 h outdoors daily).

This was followed by a detailed measurement of the contamination status in these areas by the municipalities and prefectures, and then the formulation of a decontamination plan based on the results.

The municipalities that decided to implement decontamination formulated a decontamination plan that specified the decontamination policy, implementation area, implementation method, implementing entity, priority of decontamination, and the timing of implementation, after consultation with the MOE. In the ICSA, municipalities were responsible for holding explanatory meetings for residents, reaching consensus with residents, and placing orders with contractors. To perform these tasks promptly, it was necessary to secure funds to implement decontamination projects and to assign human resources to formulate plans and coordinate with residents (establishing a department in charge of decontamination, if necessary). However, since not all municipalities had sufficient human and financial capacity, it was necessary to obtain external support for radiation risk mitigation, decontamination technology, and communication, as appropriate (Institute for Global Environmental Strategies [213]). Some municipalities formulated decontamination plans based on the Emergency Basic Policy on Decontamination and proceeded with decontamination prior to the enforcement of the Act on Special Measures; these municipalities had generally switched to a plan that coincided with the full enforcement of the Act on 1st January 2012 and implemented decontamination.

In the ICSA, preparing a decontamination plan and establishing a system to implement the plan differed from municipality to municipality and was not a straightforward task. In the case of a city with a large population like Fukushima City, the number of city employees is also large, making it easy to create a system for decontamination and to take prompt action immediately after the disaster [213]. Recognizing that it is important to build consensus with residents to proceed with the decontamination, municipalities such as Fukushima City have increased the involvement of residents from the planning stage of decontamination [209]. The cities, towns and villages in Fukushima Prefecture were also severely damaged by the earthquake and tsunami that led to the F1NPP accident and had to devote manpower and time to reconstruction and support for the victims. Even if a new department in charge of radiation control and decontamination could be established, it might be difficult to smoothly measure contamination, formulate a decontamination plan, consult with the MOE, and coordinate with residents [213].

Decontamination in the ICSA was completed in 80 municipalities by the end of March 2017. Although the period for preparing the decontamination plan was extended in 12 municipalities for the decontamination of some parts of roads and forests, ICSA decontamination was completed in all 92 municipalities by March 2018.

V.3. CHALLENGES ENCOUNTERED IN THE PROCESS OF THE DECONTAMINATION PROJECTS

The following are the challenges encountered in decontamination projects, mainly as listed in 'Decontamination Projects for Radioactive Contamination Discharged by Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station Accident' released by the Editorial Committee for the Paper on Decontamination Projects [209] and IGES Discussion Papers [213, 214].

V.3.1. Unprecedented large-scale decontamination of national land

The decontamination work in residential areas is one of the largest projects of its kind in the world. Because this was the first experience for the Japanese government, it had to proceed tentatively without sufficient technical knowledge or systems in place. With the start of very large-scale areal decontamination, the issues became securing a large number of workers and ensuring the quality of decontamination work through their occupational safety and decontamination training. The decontamination project in the SDA turned out to be extremely difficult, with a large number of projects to be implemented simultaneously by each municipality in a short period. Progress was also affected by the fact that the infrastructure had not been restored in some of the affected areas and was restricted during the winter because of snowfall.

V.3.2. Sharing goal of decontamination project

The long-term goal under the decontamination policy is to reduce additional annual exposure to 1 mSv or less through radioactive decay, natural factors, and decontamination. An intermediate reference level between 1 and 20 mSv/year could have been selected, but no specific value was given, and it was difficult to provide a reasonable explanation for selecting anything other than the minimum exposure option to the residents for the range of values. Therefore, 1 mSv/year was set as the long-term target. Because an annual exposure of 1 mSv has been recognized as a 'safe' level by the general public, an expert mission team from the IAEA encouraged the government to increase its efforts to explain to the public that this level of additional radiation per year cannot be achieved in a short time by decontamination alone [215]. In addition, there was a widespread perception that the additional dose of 1 mSv per year (or 0.23 μSv/h, which was the air dose rate adopted for convenience and safety under specific lifestyle conditions) could be achieved by decontamination alone, so the value of 0.23 μSv/h was taken as a target for decontamination. The goal of 'achieving 1 mSv per year' or 'restoring the area to its pre-accident state' became the default. This placed an unreasonable burden on the decontamination process, thus transforming the original objective of evacuating the population as soon as possible and ultimately prolonging the evacuation process. The decontamination plans formulated in August 2011, before the decision on the immediate basic decontamination policy, set targets such as 'halving the radiation dose at facilities where decontamination has been implemented'.

V.3.3. Determination of decontamination areas

The determination of areas for decontamination was based solely on the additional dose from external irradiation, which was estimated based on the air dose rate with, again, the following assumptions: (1) individuals spend 16 h inside a house and 8 h outside every day, and (2) the shielding effect of a wooden house reduces exposure inside to 0.4 times that outside. Under these assumptions, the actual radiation dose is generally considered to be less than the estimated values. The single estimation method proposed by the government seems appropriate given the lack of actual measurement data during the initial stages after the accident. However, during the recovery stage, as scientific evidence accumulated, it was important to understand or estimate realistic doses for those who wanted to make decisions based on their radiological protection or return to affected areas.

V.3.4. Obtaining consent to start decontamination and secure temporary storage sites

The need to secure a temporary storage site (Fig. 18) and obtain the consent of landowners and other concerned parties prior to the implementation of decontamination significantly impacted the progress of the project. Obtaining consent in the SDA was extremely difficult under circumstances when residents were scattered all over the country and forced to live as evacuees. There were cases where decontamination was not successful because not all residents were in favour of decontamination. For example, some residents refused to allow decontamination because they did not want to destroy the landscaping around their house, in which they had invested much time and effort. There were cases where decontamination progressed smoothly because it was easier to obtain agreement and cooperation from the residents when the decontamination was implemented by the local municipality. On the other hand, the degree of contamination and the population affected differed from municipality to municipality, and in some cases, it was difficult to formulate a decontamination plan because of a lack of agreement with residents on the scope of decontamination and the decontamination methods.

Fig. 180. Examples of temporary storage sites found in Fukushima.

For the decontamination to proceed, it was important to select a local, temporary storage site for contaminated waste and soil. Early in the process, the government selected candidate sites for temporary storage, but sometimes a plan could not proceed because of strong opposition from local residents. As of July 2012, only 20 of the 111 cities, towns, and villages targeted for decontamination had begun to set up temporary storage sites, and by February 2013, 20 of the 40 cities, towns, and villages in Fukushima Prefecture still lacked temporary storage sites [213]. According to an interview with municipal officials, the reasons given for not agreeing to set up temporary storage sites included ‘concerns about prolonged storage’, ‘environmental degradation’, ‘lack of suitable sites’, and ‘concerns about harmful rumours’. At that time, the prospects for the interim and final storage facilities were uncertain, and there was a deep-rooted concern that even if an interim storage facility could be established, it would become a permanent facility, so it was not easy to reach an agreement with local residents on the establishment of a temporary storage facility [213].

Because of a lack of experience in participatory decision-making, in many cases, communication was one-sided, with the government simply telling the residents what it had decided, and there was some opposition from the residents [214]. In some cases, residents received a message that the government was leaving the establishment of a temporary storage site up to the residents, even when there was a forum for discussion among residents so that they could decide independently on the establishment of a site [216]. To overcome these situations, the municipalities started by building trust through risk communication, entrusted the decision-making on temporary storage sites to the residents, and secured temporary storage sites in cooperation with the residents [209]. This resulted in accelerated decontamination focusing on the decontamination of residential neighbourhoods by securing temporary storage sites through citizens' collaborative efforts rather than government initiatives [217].

V. 3.5. Delays in decontamination

In consideration of the reduction of exposure to residents and the return of residents to the affected areas, the duration of the decontamination work had to be as short as possible. The progress of decontamination in the affected areas varied with location. This was because some municipalities started decontamination before the guidelines were prepared, there were differences in contamination levels, there were staff shortages due to the response to the earthquake and tsunami, and there were differences in the number and composition of evacuees and industrial structures. As mentioned above, it was not easy to secure sites for the temporary storage of the large amounts of waste generated by the decontamination or to obtain the consent of local residents, which, in turn, delayed the implementation of the decontamination project [214]. An agreement on the establishment of a temporary storage site influenced the decontamination and the status of the project; those municipalities that succeeded in setting up temporary storage sites under the situation in each area proceeded with decontamination relatively smoothly.

Several factors hindered the promotion of decontamination in Fukushima Prefecture, especially in the ICSA. Those factors included “distrust of public administration,’ ‘lack of understanding about decontamination,’ ‘concerns about temporary storage sites and interim storage facilities,’ ‘selection of decontamination technologies,’ ‘how to share information,’ ‘lack of experience in the participatory decision-making process,’ and ‘vertical administrative structure and the lack of horizontal collaboration’ [214].

V.3.6. Communications and public perception of radiation risks

At many of the decontamination sites, residents' dissatisfaction with and distrust of the decontamination policy became an issue. In some cases, the change in appearance resulting from the removal of soil and vegetation had more of an emotional impact than the effect of dose reduction [218]. This dissatisfaction can be explained by the fact that the purpose of decontamination was not understood or shared among stakeholders. On the other hand, the lack of explanation of the decontamination methods, constraints, and expected results also led to residents' dissatisfaction. In this regard, some municipalities reported the measured ambient dose rates before and after decontamination to the residents and asked for their understanding.

Some residents were dissatisfied and felt that the differences in the progress of decontamination among municipalities were unfair [209]. To mitigate this dissatisfaction and sense of unfairness among residents and to promote decontamination acceptable to residents, it is important to consider the means of communication between the government entity responsible for decontamination and the residents. The government made various efforts to improve communication with the residents. The Ministry of the Environment [219] released the ‘Collection of Examples of Good Decontamination Efforts’ introducing a case where the order in which decontamination was carried out in a region was decided through collaboration between the government and residents.

At the time of the accident, there was insufficient general knowledge among the public of the effects and risks of radiation. This, combined with the repetition of incomprehensible explanations such as ‘there is no immediate effect on human health,’ caused the public to grow anxious and distrustful of the government. It was difficult for the government and experts to convince the residents of the benefits of decontamination by simply explaining scientific and technical matters in a one-sided manner.

The distribution of radiation levels was uneven, and people have different concerns about the effects of radiation. Even in the case of low radiation doses, the residents' feelings about decontamination varied. According to a survey conducted by local governments in low-dose areas where areas with locally high radiation doses had been decontaminated, some residents were concerned about limiting the decontamination to localized areas, whereas others did not wish to undergo further decontamination because they had gained a certain sense of security from previous decontamination. In a survey in Fukushima City in an area where decontamination had been carried out earlier [220] more than 70% of the respondents answered, ‘very good’ or ‘somewhat good’ out of four levels of evaluation for the implementation of decontamination; however, the most common response out of five choices regarding the results of decontamination was ‘normal’ at 27.3%, with ‘satisfactory’ and ‘somewhat satisfactory’ accounting for only 28.0% in total.

V.4. CONSEQUENCES OF DECONTAMINATION PROJECT

The decontamination project was based on the Act on Special Measures, which was enacted in August 2011. The MOE has established the necessary systems and structures for decontamination projects, including related laws and regulations and decontamination guidelines. In the SDA, decontamination started in December 2011 with the Self-Defence Forces decontaminating government offices and other locations in the evacuation area. Beginning in January 2012, decontamination was implemented on a municipal basis by construction companies, with the MOE as the contractor, and was completed in March 2017. In the ICSA, in response to requests from the residents, voluntary decontamination by the residents of schools, kindergartens, nursery schools, and parks started around April 2011 in some municipalities. Later, following the enactment of the Act on Special Measures, each municipality prepared a decontamination plan, and beginning in January 2012 decontamination was implemented by construction companies contracted by the municipality, and this was completed in March 2018.

As a result of the decontamination project, the evacuation order was lifted for 780 km^2 in the SDA, or approximately 70% of the 1150 km^2 under an evacuation order, and the additional annual exposures for residents returning to the areas where evacuation orders were lifted were generally around 1 mSv or less [221]. In the ICSA, the annual additional exposures of residents were generally confirmed at 1 mSv or less in 2016. For both decontamination areas, the long-term targets set in the basic policy of the Act on Special Measures were generally achieved, except for in the difficult-to-return zone.

In the SDA, the areal decontamination based on the decontamination plan was completed at the end of 2016. In total there were about 13 million workers involved in the decontamination project in the 11 cities, towns, and villages in the SDA, and the budget was estimated to be approximately 1.3 trillion yen (as of the end of January 2017). In total, decontamination involved 23,000 residential houses, 8700 hectares of agricultural land, 7800 ha of the forest, and 1,500 ha of roads. Of the 31,326 persons' property owners concerned, consent was obtained from 31 085. As of the end of September 2017, about 241 people had not given their consent. As of November 2017, there were 252 temporary storage sites, and approximately 9 million cubic meters of contaminated soil had been removed, of which approximately 1.6 million cubic meters had been transferred to intermediate storage or temporary incineration facilities. According to the results of monitoring implemented by the end of June 2017, the average ambient dose rates in residential areas, agricultural land, and roads after decontamination were approximately 40–60% lower than before decontamination. Ambient dose rates in forests were reduced by 27% after decontamination and by 46% in post-decontamination monitoring compared to before decontamination.

In the ICSA, there were approximately 17 million workers in total in the 92 cities, towns, and villages in the priority contamination survey areas. As of the end of January 2017, the budget was estimated to be approximately 1.3 trillion yen (approximately 1.2 trillion yen in Fukushima Prefecture and approximately 50 billion yen outside Fukushima Prefecture). As of the end of March 2017, there were 847 temporary storage sites and 150 000 on-site storage sites. Approximately 7.2 million cubic meters of soil were removed (approximately 6.8 million cubic meters in Fukushima Prefecture and approximately 400 000 cubic meters outside of Fukushima Prefecture), and approximately 1.1 million cubic meters were transferred to intermediate storage or temporary incineration facilities. The decontamination of municipalities in Fukushima Prefecture up to February 2016 resulted in a reduction of the average spatial dose rate of 42% in residential areas, 55% in schools and parks, and 21% in forests compared to before decontamination.

Focusing on the decontamination costs, a few studies evaluated the cost and effectiveness of remediation of radioactive contamination in Fukushima [222-224]. In the special decontamination areas in Fukushima, aerial decontamination would be effective for reducing the ambient dose rate to the target level in a short period in some but not all of the areas, and the decontamination cost for the basic scenario was estimated at 0.53–5.12 trillion yen for the affected areas in Fukushima Prefecture [223-224]. These studies also suggested that decontamination costs for agricultural areas account for approximately 80% of the total decontamination cost, of which approximately 60% is associated with storage. They implied that the selection of appropriate decontamination methods could significantly reduce decontamination costs, allowing more meaningful decontamination in terms of the limited budget. Although the cost and effectiveness of the different decontamination strategies is not the sole determinant, it is one of the most important attributes when developing a remediation strategy.

There were 1786 accidents during decontamination work in the SDA between 2013 and 2017 [209]. The highest number of accidents occurred in 2015. There were three fatal accidents. In the autumn of 2016, there was a series of accidents involving heavy machinery, including fatal accidents. Sawano et al. [225] reviewed the health risks among decontamination workers after the F1NPP accident and pointed out a diverse range of risks. To understand the totality of health risks among the decontamination workers, Sawano et al. stressed the importance of considering both the uniqueness of the occupational environment and the demographics of the workers, a considerable proportion of which were migrant workers from outside of the disaster-affected areas. Health risks associated with occupational hazards included radiation exposure, psychological problems [226,227], heatstroke [228], trauma and bite injuries [229, 230], and infectious diseases [231]. Health risks associated with the living conditions of the decontamination workers included high rates of alcohol consumption and smoking, obesity, and a high prevalence of non-communicable diseases such as hypertension, dyslipidaemia, and diabetes [232]. Reference [226] emphasized that for future nuclear disaster preparedness it is necessary to include the comprehensive support of decontamination workers, which includes the effective management of diseases related to lifestyle in addition to occupational hazards stemming from the unique work environment, such as radiation exposure, work-related infections, and trauma during work.

To reduce residents' anxiety and improve their subjective well-being, [233] circulated a questionnaire among residents of an affected municipality to evaluate the effects of radiation-related countermeasures such as decontamination implemented by the municipality. The information collected suggested that people who rated the decontamination process highly experienced a reduction in radiation anxiety compared to that immediately after the 2011 accident and that their satisfaction with life was high.

The delay in decontamination in the SDA led to a prolonged evacuation. According to the original plan, the decontamination project was to be completed by the end of March 2014, but because progress varied from municipality to municipality, a plan more in line with the actual situation was formulated. As a result, the prolonged evacuation caused a variety of health effects in the evacuees. A wide range of health issues caused by long-term displacement and consequent drastic lifestyle changes associated with the Fukushima nuclear accident have been reported elsewhere [234]. These health issues include not only radiation exposure, but also secondary health issues such as those related to psychological and mental health, lifestyle diseases, changes in clinical services and nursing care availability, and access to hospitals. The psychological distress among those who returned home after the evacuation order was lifted was lower than that of evacuees but still higher than the national average [235]. One of the marked changes in residents' living and social environment due to evacuation involved the increased severity of chronic diseases such as diabetes. The risk of developing diabetes after 2013 increased significantly in the evacuation areas (by a factor of 1.55–1.60) from the 2008–2010 baseline [236].

Classifying areas as decontamination and evacuation zones creates a boundary between areas and residents that are eligible for officially recognized compensation and those that are not. For some areas, there was not much difference between the ambient dose rates inside and outside the boundaries. The boundary separating the inside and outside the evacuation zone has become a boundary determining whether one is an official evacuee or not, a boundary for compensation, and a boundary of one's mind, and it has divided local governments and communities in complex ways [237]. Reference [237] pointed out that, in the case of a large-scale, wide-area radiation disaster with long-lasting effects, a 'subjective' boundary changes from person to person and place to place, further complicating the issue. Depending on a person's perception of risk, 'contaminated' and 'uncontaminated' areas, or, in other words, 'damaged' and 'undamaged' areas, change. The establishment of decontaminated areas may objectively fix this 'subjective' damage. For example, Aizu Wakamatsu City chose not to decontaminate to avoid the stigmatization as a decontamination area.

Prejudice and discrimination against evacuees over radiation exposure, and compensation at evacuation sites has become a social issue [238]. According to a report by MEXT in 2017, there were 199 confirmed cases of bullying against children who evacuated outside of Fukushima Prefecture after the nuclear accident, 13 of which were related to the evacuation. For example, a male elementary school student who evacuated outside of Fukushima was punched, kicked, and called 'germs' by his classmates from the school he attended as an evacuee and was reportedly ordered to pay the bullies 1.5 million yen to avoid physical abuse [239]. One reason why this happens is thought to be related to the fact that knowledge about radiation has not yet penetrated the general public, and in Japan, because of the Fukushima accident, continuous and sustained education about radiation is necessary [238]. This education will serve as important baseline information for future education after the nuclear disaster.

The prolonged evacuation resulted in a decline in the number of people returning to their original locations, which in turn led to changes in the social structure of the affected areas. After the evacuation orders were lifted, some people wanted to go home, but others did not. As a result, things such as the everyday lifestyle, local culture, and traditions were lost. According to a survey conducted in 2019, of the residents evacuated from Futaba, Okuma, Tomioka, and Namie towns, 50–60% have indicated that they will not return (Table 13). The reasons given by those who returned included that they felt at ease, radiation levels had been reduced, the functions of the municipality had resumed, and the safety of tap water had been confirmed [240]. The reasons given for not returning included that they had already established their social infrastructure at the evacuation site, they were concerned about the medical environment in their hometown or city, and the evacuation site was more convenient. In surveys conducted soon after the accident, a large percentage of people did not return because of radiation levels, but now that decontamination has been completed, this is not an important reason. This suggests that decontamination has had a certain effect in reducing anxiety about radiation. For some time after the accident, there was no prospect of the evacuation order being lifted. The evacuation process was prolonged without any knowledge about the possibility of returning home. This suggests that residents have already formed a new foundation for their lives in the areas to which they were evacuated, and no longer intend to return. Justification for further input of resources, such as further decontamination, has to be examined in light of the residents' intentions to return to their homes.

TABLE 13. FISCAL YEAR 2019 SURVEY OF PUBLIC OPINION AMONG RESIDENTS (REGARDING INTENT TO RETURN HOME [240]

	Number surveyed	**Already returned (%)**	**Want to return (%)**	**Cannot decide (%)**	**Will not return (%)**
Futaba	1402	-	10.5	24.5	63.7
Okuma	2090	1.8	10.6	26.6	59.9
Tomioka	2932	7.5	8.2	14.2	49.0
Namie	3546	6.5	11.5	26.1	54.8
Katsurao	292	28.4	19.5	18.2	31.8
Minami-soma	2370	63.2	5.8	9.0	13.4
Kawauchi	249	36.5	6.4	9.2	8.8

V.5. LESSONS LEARNED

This case study covers a limited scope of the extensive work of remediation of off-site areas affected by the releases from the Fukushima Daiichi NPP. The subject as a whole will of course be a theme of debate and discussions for quite a long time. What is unequivocal is that due attention needs to be paid with the so many lessons learned in different fields. Definitively, decision making is one of such areas that deserves close attention from different parties such as policy makers, governmental authorities, scientific community, and regulators. Individuals of the general public can also be added to this list as they will be key parties in these overall discussions, after all decisions to be made will ultimately affect their lives.

With the above in mind, the lessons learned presented in this item are not meant to be comprehensive, but they indicate some points that can orientate similar processes also in different situations.

- While it is important to set clear criteria for setting boundaries for areas requiring decontamination, it is also important to consider reflecting the actual situation when realistic data is available. The decontamination in Fukushima aimed for 1 mSv as the long-term target for the additional exposure dose, which is the low side of the 1–20 mSv per year exposure range under the existing exposure situation recommended by the ICRP. The determination of 1 mSv per year as the additional exposure limit was based on the specified condition that the dose could not exceed 0.23 μSv/h, a value on the safe side that replaced the annual value for convenience, using a specific lifestyle. Because there was only limited information at the time this criterion was being considered, the value was used as is to be on the safe side. This value was only a long-term target, but the fact that 0.23 μSv/h was perceived as a decontamination target caused confusion. As scientific knowledge accumulates and realistic doses become clearer, it will be important to determine how to draw the boundaries when preparing evacuation orders for future nuclear disasters. The method of drawing these boundaries will have a significant impact on the cost of decontamination, the area to be covered, and the future of the residents living there;
- The scope of environmental contamination by radioactive materials caused by the Fukushima accident was vast and included lands with various uses such as residential areas, farmland, and forests, and it was necessary to consider and implement different decontamination methods simultaneously. With such a wide range of stakeholders, including the national government, municipalities, decontamination companies, and residents, it was necessary to conduct a study with such a wide scope and the relationships between people and their trust became an important factor that greatly affected the implementation of the project;
- When decontaminating private land, it is essential to obtain the consent of the landowner. In Fukushima, it was not easy to obtain the landowners' consent, which greatly affected the preparation period for decontamination. It is important to carefully explain the purpose and effect of decontamination and to work with the local government and residents to gain their understanding of the decontamination process;
- It is important to use an interactive process in decision-making regarding decontamination methods, securing temporary storage sites, and implementing the decontamination plan. As trust in the government had been eroded, it was difficult to gain the understanding of landowners and local residents when the government unilaterally declared how to proceed with the decontamination, and this sometimes led to protests. Sharing information on decontamination and temporary storage sites as a common issue in the community, as well as safety, and exchanging opinions between residents and decontamination practitioners can lead to the cooperation of local residents, which in turn can facilitate the securing and management of temporary storage sites;
- Decontamination in Fukushima generated a large amount of removed soil. Decontamination methods to reduce radiation levels include not only soil removal but also inversion ploughing and topdressing. The choice of such methods may lead to a significant reduction in decontamination costs. It is also important to consider the possibility of reusing the large amount of soil generated as a soil resource soil after appropriate treatment and volume reduction;
- It is essential to properly explain and communicate the purpose, process, and goals of decontamination to residents. In Fukushima, decontamination aimed for the return of evacuated residents while maintaining their livelihoods. Communication with landowners is especially important in decontamination that involves the restoration and maintenance of residents' lifestyles;
- Decontamination strategies are not linked to the strategies for personal dose measurements, compensation, or evacuation because of the vertically segmented administrative system in the government;
- It is important to consider the health risks and social and ethical impacts arising from evacuation and other operations associated with decontamination;

— Radiation education is important not only for the affected areas but also for the more remote areas that receive evacuees from the affected areas and even for the entire country. Prejudice and misunderstanding of Fukushima by those who accepted evacuees caused undue stress for the affected residents.

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ABBREVIATIONS

ANP	Analytic Network Process
BR	Regulation Basis
CL:AIRE	Contaminated Land: Applications in Real Environments
CSM	Conceptual Site Model
CBA	Cost Benefit Analysis
ELD	Environmental Liability Directive
ER	Environmental Remediation
ICRP	International Commission on Radiological Protection
ICSA	Intensive Containment Survey Area
INSIDE	INfluence based deciSIon guiDE
ITRC	Interstate Technology Regulatory Council
LCA	Life-Cycle Assessment
MAESTRI	Management Systems Supporting Environmental Remediation Projects
MAWP	Multi-Annual Work Program
MCDA	Multi-Criteria Decision Analysis
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MS	Member States
NORM	Naturally Occurring Radioactive Material
SCORE	Sustainable Choice of Rem
SDA	Special Decommissioning Areas
SMCE	Social Multi-Criteria Evaluation
SOCRATES	SOcial multi-CRiteria AssessmenT of European policieS
SuRF-UK	Sustainable Remediation Forum – United Kingdom

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