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Part 1 Cost-Benefit Analysis

Lead Authors: Astrid Liland (DSA/NMBU), Andrei Goronovski (UT)

With contributions from: Ståle Navrud (NMBU); Alan Tkaczyk (UT); Danyl Perez-Sanchez, Silvia German Prats, Roser Sala (CIEMAT); Madeleine Barbru (DSA)

Reviewer(s): Pascal Crouail (CEPN); Marie Simon-Cornu (IRSN); and CONCERT coordination team

Part 2 - Multi-criteria decision analysis

Lead Authors: Catrinel Turcanu, Lieve Sweeck, Nathalie Vanhoudt, Bieke Abelshausen (SCK•CEN)

Reviewer(s): Astrid Liland (DSA); Pascal Crouail (CEPN); Marie Simon-Cornu (IRSN); and CONCERT coordination team

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Abstract

This report documents work undertaken in CONCERT subtask 9.3 (TERRITORIES project), more specifically the TERRITORIES sub-task 3.4 Socio-economic analysis. It presents two different ways of evaluating remediation options for radioactively contaminated sites. Part 1 presents a Cost-Benefit Analysis framework which is illustrated by application to a Spanish NORM site. Part 2 presents a Multi-Criteria Decision Analysis framework which is illustrated by application to a Belgian NORM site.

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Preamble

The TERRITORIES project aims at an integrated and graded management of contaminated territories characterised by long-lasting environmental radioactivity, filling in the needs emerged after the recent post-Fukushima experience and the publication of International and European Basic Safety Standards. A graded approach, for assessing doses to humans and wildlife and managing long-lasting exposure situations (where radiation protection is mainly managed as existing situations), will be achieved through reducing uncertainties to a level that can be considered fit-for-purpose. The integration will be attained by:

- Bridging dose and risk assessments and management of exposure situations involving artificial radionuclides (post-accident) and natural radionuclides (NORM),
- Bridging between environmental, humans and wildlife populations monitoring and modelling,
- Bridging between radiological protection for the members of the public and for wildlife,
- Bridging between experts, decision makers, and the public, while fostering a decision-making process involving all stakeholders.

This project will interlink research in sciences supporting radiation protection (such as radioecology, human or ecological dose and risk assessments, social sciences and humanities, etc.), providing methodological guidance, supported by relevant case studies. The overall outcome will be an umbrella framework, that will constitute the basis to produce novel guidance documents for dose assessment, risk management, and remediation of NORM and radioactively contaminated sites as the consequence of an accident, with due consideration of uncertainties and stakeholder involvement in the decision making process.

Work Package (WP) 3 of the TERRITORIES project focuses on “Stakeholder engagement for a better management of uncertainty in risk assessment and decision-making processes including remediation strategies”. It has as an overall objective to analyse the decision-making processes in long-lasting radiological exposure situations, taking into account all components of risk assessment, with two key points: management of uncertainties and stakeholder engagement.

Task 3.4 aims at providing support for the evaluation of remediation strategies using novel methods of socio-economic and policy analysis for a selection of real and/or hypothetical scenarios (collected and described in Tasks 3.1 and 3.2). Two methodological approaches will be developed. The first approach is based on valuation of the human and environmental impacts, both market and non-market losses (e.g., landscape degradation by waste storages, recreational value of access-restricted forests, value of preserving a sustainable environment for future generations, cultural behaviours). Non-market losses include considerations of the public’s appreciation (and acceptance) of various possible choices through the use of valuation methods such as willingness-to-pay and choice experiments. The second approach is multi-attribute analysis, in which the evaluation criteria are expressed in their natural units, instead of being subject to translation to a unique, monetary scale. As a sensitivity analysis, calculations performed with both approaches will be tested with a reasonable range of expected parameter values (taking into account results from WP1 and WP2).

Within this context, the work undertaken in CONCERT sub-subtask 9.3.3.4 (Task 3.4 of the TERRITORIES project) dealt with two types of socio-economic analyses: Cost-benefit analyses (CBA), further detailed in part 1 of this document, and Multi-criteria decision aiding (MCDA), further detailed in part 2 of this document.

PART 1 - COST-BENEFIT ANALYSIS

1. Introduction

Accidents at nuclear installations can result in release of artificial radionuclides and severe radioactive contamination over small or large areas. Contamination by NORM can be a problem in industries using natural ore, due to mining or other activities that enhance natural radioactivity to a level of possible negative health or environmental impact. The severity and long persistence of radioactive contamination challenges the affected communities in many ways. It is not just a question of radiation dose – it affects environment, economy, production, living conditions and health. It is thus a societal problem and the management strategy needs to take account of social, ethical and economic consequences along with the radiation impact.

Problems are considered to be of a social character if they remain unsolved or are mitigated in an inadequate way if they are left to the private market (DFØ, 2018). Examples include the response to contamination events, for instance nuclear post-accident areas or NORM sites. Such problems call forth a public intervention. The reasons are several: a responsible polluter according to the polluter-pays principle may be lacking; the knowledge of radiation issues and countermeasures is non-existing or very limited in local communities; specific expertise and instrumentation is needed to map the contamination levels; a harmonisation of countermeasure implementation in all affected areas is preferable for public acceptance, etc.

Cost-benefit analyses (CBA) are used to identify and highlight possible impacts from implementing public measures that involve large public spending and that might affect a range of stakeholders. CBA is aiming to consider all of the costs and benefits of the society as a whole, thus by some referred to as social cost-benefit analysis (Boardman et al, 2014). CBA can determine if a mitigating option has net benefit for the society, and can be used to rank various possible options to assist in choosing the best option (or combination of options) to address the problem. It can also be used to decide if any option should be implemented at all, unlike other approaches which can only choose between different alternatives (OECD, 2018). When applied to radioactively contaminated sites/areas, the CBA can be seen as a constructive way of addressing the ALARA principle (ICRP, 2007) which states that exposures should be as low as reasonably achievable, social and economic factors taken into account. Since CBA treats all costs and benefits for all affected interest groups / stakeholders, it will address not only the economic factors, but also the social and, indeed, ecosystem effects of implementing mitigating options or not.

We here address CBA as an *ex-ante* analysis, i.e. an analysis that is to be performed prior to taking a decision on which options(s) to implement. There are several good reasons for performing CBA, including:

- Maximizing welfare from limited public resources through efficient resource management;
- Systematic categorization of all possible impacts for selected stakeholders;
- Establishing a sound decision making basis to rank and prioritize between possible measures;
- Discarding unprofitable measures at an early stage; and
- The basis for decision-making is open and transparent to the public.

Even if CBA is well acknowledged and used for a variety of cases, there are few examples of how CBA has been used to assess remediation options for radioactively contaminated sites. A search on SCOPUS on June 8th 2018 with the words *Cost benefit analysis*, revealed 160,718 articles and reviews, while *Cost benefit analysis AND environmental remediation* revealed 476 articles and reviews. For the search words *Cost benefit analysis AND environmental remediation AND radioactive*OR nuclear*, however, only 37 articles and reviews were retrieved. 17 of these concerned natural radon in dwellings, which is out of scope for the work in TERRITORIES. Only 5 articles actually addressed (at least partly) CBA for environmental remediation of radioactively contaminated sites.

This report is a short and applied guide on how to use CBA as a decision support tool for evaluating mitigating options for sites/areas contaminated by NORM or from a nuclear accident. It will not elaborate on the economic theory behind such an approach, since this can be explored in text books like Boardman et al (2014): Cost-Benefit Analysis – Concepts and practice, and publications like OECD (2018): Cost-Benefit Analysis and the Environment.

2. The basic steps of Cost-Benefit Analysis

There are eight basic steps in a CBA, see Figure 1. The description of each step is given below along with examples to illustrate the process. Whenever possible, we have used examples from radioactively contaminated areas / sites. The approach has been applied to the Huelva NORM site in Spain, to illustrate the process, see chapter 3.

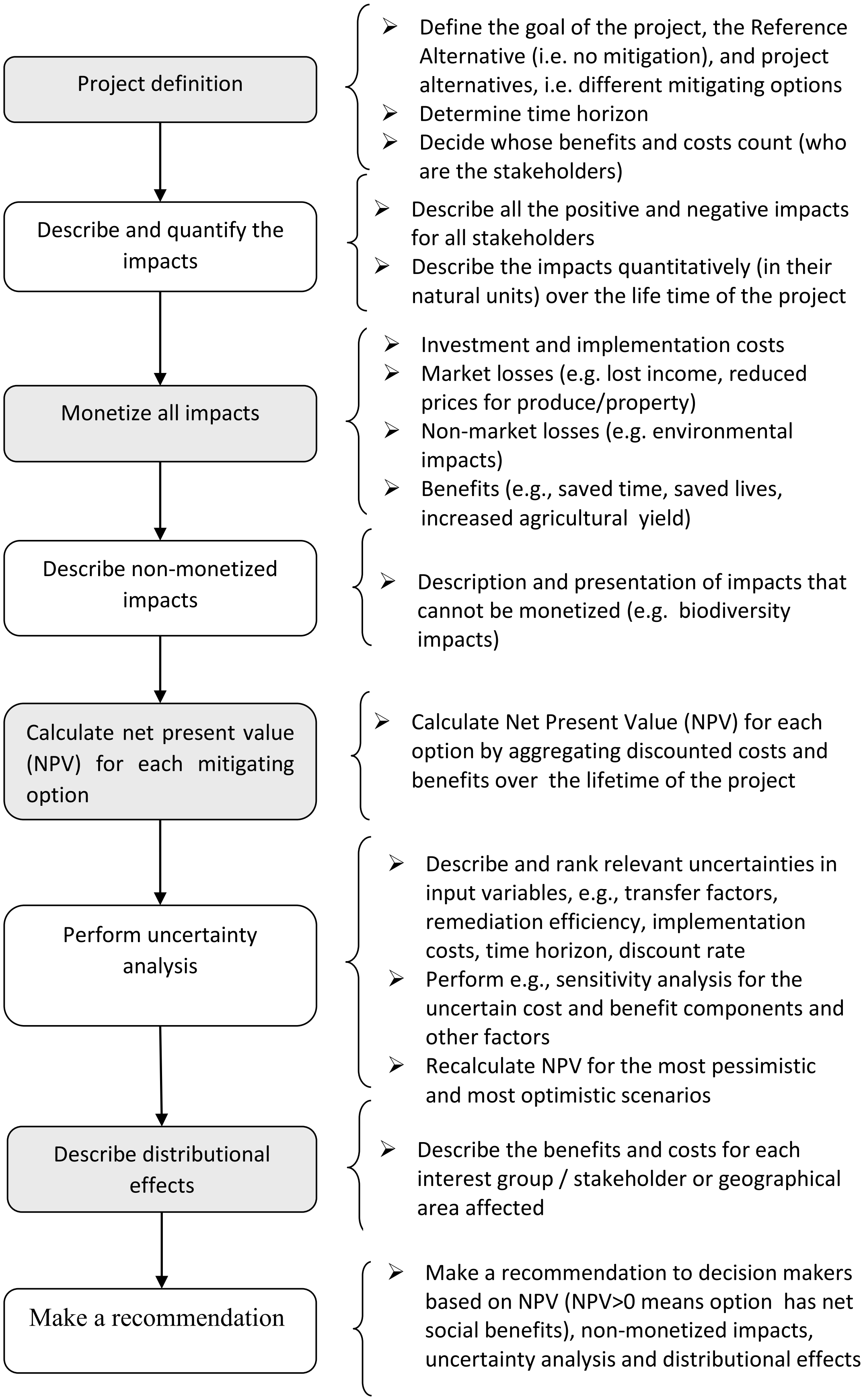

Figure 1: The main steps in a cost-benefit analysis (CBA)

2.1 Project definition

The process starts with a **problem formulation** to elucidate that the problem is of a magnitude and severity that requires public intervention. Then the project must be defined, starting with the *Reference Alternative* (often also termed *Zero Alternative)*. This is the development without the project, which is often the "Do nothing" option. This involves describing the current situation and how will it evolve over time if nothing is done to mitigate it. Impacts (both benefits and costs) of project alternatives, in this case mitigation options, will be assessed relative to the Reference Alternative.

The **goal** of the project must be defined, i.e., a desired result or future status to be achieved. It should not be set in a very narrow manner but allow several options to be investigated to find the solution with the highest net social benefit.

The next step is **identifying possible project alternatives**, which here are the mitigating options. All relevant options that can achieve the stated goal, either as stand-alone options or as a combination of options, should be identified. If there are many available options, those with clear restraints could be sifted out so that only relevant options are included in the further analysis. The reason for non-inclusion should be justified.

Only options that are likely to reach the stated goals, and where the benefit are likely to outweigh the costs, should go further in the analysis. Then one should **describe the chosen options, i.e.** what will be done, how, when and by whom.

The final step is to **decide whose benefits and costs count** in the analysis. OECD (2018) defines benefits as increments in human well-being (or 'utility' in economic language), and costs as a reduction in that well-being. Who will be affected by the mitigating options in a positive or negative way? It could be the industry, neighbours, farmers, consumers, the public etc. depending on the scenario and the relevant mitigating options. This will always be case specific.

EXAMPLES
The goal of the project

If the stated goal is very narrow, e.g., "The residual radioactivity in soils should be below 100 Bq/kg", then the process will be a *cost-effectiveness analysis* and not a CBA. In a cost-effectiveness analysis a number of mitigating options are compared to see which one can reach the goal for the lowest cost. This is an appropriate method when there are strict clean-up criteria in e.g., legislation that you need to comply with.

In CBA, however, it is preferable to define goals that are not so narrow, e.g., "The residual dose to future inhabitants on the site should be in the range 1-20 mSv/y". The analysis of different mitigation options could result in option A having a residual dose of 3 mSv/y, option B having a residual dose of 14 mSv/y and option C 6 mSv/y, for instance. Each of the options A, B and C would also have different associated costs and benefits for a number of stakeholders (who could also vary). All this should be transparent for the decision makers when a recommendation is given.

Sifting out mitigation options with clear constraints

In the event of a nuclear accident, large agricultural areas could be contaminated by radionuclides so that the food produced will exceed the food intervention levels for human consumption. If the stated project goal is that all food produced in the future should be below the food intervention level, a range of possible mitigation options can be considered to achieve this goal. Examples (non-exhaustive list) are: deep ploughing, using potassium fertilizer, changing to a different crop, food processing, and dilution. Experience from the FARMING project (Nisbet et al, 2005) showed a divergence between European countries concerning practicability and acceptability of agricultural mitigation options due to differences in geomorphology, climate, land management, infrastructure, consumer confidence, socio-political context and culture. Dilution, in the sense of mixing contaminated produce with clean produce to achieve a product that was below the food intervention level, was for instance an unacceptable option for some countries due to ethical considerations. In such a case, dilution could be sifted out as an unacceptable option early in the process, and not taken further in the analysis.

2.2 Describe and quantify the impacts

In this part of the analysis, all the positive and negative impacts for all interest groups / stakeholders from implementing the mitigation options should be identified and described. An impact is defined as a change compared to the *Reference alternative* (DFØ, 2018). The types of impact will be scenario specific. Start with the key impacts, and devote most of the time and resources to those key impacts in the rest of the analysis.

The key impacts should be described for relevant affected interest groups: To which degree are they impacted; will it be in a direct or indirect way; how will they be impacted?

The impacts should be described quantitatively (in the units they naturally occur) over the life-time of the project. For public environmental projects the usual time horizon is long and can be of the order of decades (European Commission, 2014). Typically, the project time horizon would be 30-40 years which means you would look at benefits and costs over that whole period. CBA is typically used for large (often public) interventions where the implementation period is long (years) and where the benefits after completion would be apparent for several decades. However, a different time horizon may be proposed if justified.

Typical negative impacts from radioactive contamination could be increased risk of cancer, pollution of the environment, restriction on access or use of an area, decreased property prices, and loss of livelihood. These could be relevant during or after implementation of mitigating options. All costs related to the implementation of the options are also seen as negative impacts.

Positive effects from implementing mitigating actions could be reduced cancer risk, reduced pollution, reinstated trust in produce, area released for public use, restored habitat for flora and fauna etc.

At this stage, the impacts are described in their natural units, e.g., leakage of radioactive nuclides (Bq/L), activity concentrations in foodstuffs (Bq/kg), lost income for a farmer due to food restrictions (€), doserates to biota (µGy/h), averted doses to humans (mSv), worker doses when implementing options (mSv/d), change in property prices (€), area with restricted use (m^2) etc. All these impacts should be quantified on an annual basis for the whole project time horizon.

The impacts should also be quantified using statistics such as number of inhabitants in the affected area, food production quantities, average property prices in the area, average wages etc.

EXAMPLE

Belarus was heavily contaminated by the Chernobyl accident in 1986. Potassium (K) fertilising was one of the mitigation options used to reduce the uptake of radiocaesium ($^{134+137}Cs$) in agricultural plants. K is an essential element for all plants. K and Cs have similar chemical properties, and plants may take up Cs as a substitute for K. But if there is abundance of K in the soil, the plants will largely take up K instead of Cs. The use of K fertilizer was thus reducing the uptake of Cs to the plants, but it also had another positive effect. The fertilising increased the yield on the agricultural plots. In CBA, this positive side effect should also be described and quantified, for instance an increase of 1 tonne of vegetables per year for a given agricultural plot which benefits the producers or owners of that plot.

2.3 Monetize all impacts

Once all impacts have been identified, a monetary value has to be assigned to them. Some of the impacts can be monetized in a relatively straightforward manner with market prices (e.g., price of decontaminated land that is returned to normal use, lost income, property prices), while others (e.g., human health impacts, recreational use of an area, environmental impact) do not have direct market value and require different treatment. For the latter indirect methods of valuation must be employed to assign a monetary value to the impacts. The final aim of this stage is to present all the relevant costs and benefits in the same monetary unit as far as possible, in order to be comparable. There may be some impacts, though, where a monetary value cannot be assigned. This is addressed in chapter 2.4.

2.3.1 Valuing impacts using market prices

For any good or service where there is an existing market, the impact (cost or benefit) can be valued by multiplying the physical amount by the market price; e.g. a contaminated site is cleaned up allowing for the site to again be used for agricultural production. However, this assumes that the market prices are not affected by the project, and that the market price are not distorted by imperfections in the market like oligopoly or monopoly instead of perfect competition, and taxes/subsidies for financial purposes rather than to correct for negative /positive external effects. If these assumptions do not hold, corrections have to be made.

All impacts that can be valued using market prices should be assigned a monetary value, usually at an annual basis, for the whole time horizon of the project.

Investment costs

An important part of the total costs would be the investment cost that are required. These costs usually consist of three major parts (1) start-up, (2) implementation and (3) maintenance costs within a given time period.

The start-up costs would include mainly the preparatory phase of the project focusing on the planning, labour training, technical or scientific development, etc. The implementation costs would focus on the costs for performing the mitigating actions such as equipment, labour, fuel, and waste conditioning. It is important to mention here, that labour is considered as a cost of the project. In countries with close to full employment the social cost of labour is the wage rate plus the social costs of employment. The creation of employment is considered a benefit only in the case of large national (or regional) unemployment. Then the opportunity cost of employment would be lower than the wage rate plus social costs of employment. This would reduce the costs of labour.

The maintenance costs are the recurring costs that can last for the whole time horizon. For radiological mitigation projects these can cover the costs of the waste interim storage (if needed), the final waste disposal, monitoring costs, annual consumables and compensations (if any). One example could be the annual use of potassium fertilizer to reduce the uptake of radioactive caesium from soil to plants in contaminated agricultural fields. Both the purchase of fertilizer and the extra labour necessary would count as recurring costs.

When calculating the cost of labour in countries with close to full employment, the gross wages including tax, social costs and employers' national insurance contributions should be used, while for goods the prices should be without value-added-tax (VAT) and customs fees (DFØ, 2018).

If the mitigating actions will be financed by public funds, there is an additional social cost to be added. In Norway for instance, 20 % is added to the financial investment costs if public funds are used, to reflect the costs of collecting the money through the tax system. These costs vary between countries and the additional percentage should be chosen according to the country where the remediation is to be performed.

2.3.2 Valuing impacts without market prices

Some goods do not have a market price, such as ecosystem services, public health, cultural heritage and environmental quality (i.e. air, water and soil quality), and thus other methods than market prices have to be applied to value them. Previously, such impacts were not included in CBA (e.g., ICRP, 1983) or only treated in a qualitative way. Particularly the last three decades, economists have developed methods to assign values (termed *shadow prices)* to such goods.

These methods are based primarily on the willingness-to-pay (WTP) principle where different studies can be undertaken to assess what (directly or indirectly) affected households are willing to pay to achieve a positive impact (benefit) or to avoid a negative impact (cost). The opportunity cost principle is also used in e.g. the replacement costs method (see below).

A significant amount of studies has been performed to quantify shadow prices for common benefits, like reduction of health risks, increased life expectancy or reduced travel time and sufficient evidences exist to assign monetary values to these goods. For instance, many countries have defined the value of a statistical life (VSL) to be used in CBA. However, it should be kept in mind that such results are often country specific as WTP depends on household incomes which vary across countries. As an example, the VSL is 4 500 USD in Bangladesh while 3 600 000 USD is recommended by the OECD for the European Union (Lindhjem and Navrud, 2015; Lindhjem et al, 2011; OECD, 2012). Similar national data may exist for reduction of health risks, reduced travel time, improved safety conditions, etc. Whenever such nationally defined values are available, they should be used to monetize non-market impacts in a CBA.

In case of remediation of a radiologically contaminated site for instance, the reduced radiological exposure to humans can be converted to save statistical lives based on the risk estimates from ICRP (2007).

At the same time, many environmental impacts do not have defined nationally agreed unit values that can be used. In such cases new valuation studies need to be performed. Different primary valuation techniques are described below. However, performing such new studies may be time-consuming and costly so values from previous primary valuation studies (see e.g. Environmental Valuation Reference Inventory (EVRI) at www.evri.ca containing more than 4 000 valuation studies) valuing similar environmental or public health impacts could be used. However, such “benefit transfer” (or more general “value transfer” as both benefits and costs can be transferred) from a study site to the policy site where the CBA is undertaken adds uncertainty to the analysis (Navrud, 2004; Navrud and Ready, 2007).

Moreover, these non-market goods often require site-specific valuation among the local population. As an example, decontamination of a lake might be of a great significance for local people for recreational purposes, while for people living far from this area this might have close to zero benefit. At the same time people living close to another contaminated lake might show lower interest in its decontamination, as there are plenty of other recreational alternatives in the form of water reservoirs nearby that might fit the same purposes. Therefore, site-specific data might be important.

Environmental Valuation methods can be divided into Stated Preferences (SP) and Revealed Preference (RP) methods. In SP methods people are asked in surveys to state their preferences for hypothetical changes in the environmental good in question, whereas in RP we observe people´s behaviour in markets that are related to the environmental good in question (e.g. markets for transportation to a recreational area in the Travel Cost method, and housing markets in Hedonic Pricing, where environmental quality is part of the value of the house or apartment).

A. Stated Preference Methods

i) Contingent valuation

Contingent valuation (CV) is often referred to as a ''stated preference'' method, as opposed to the revealed preference methods. CV is a widely used method to value non-market benefits, as it is able to capture both use values and non-use values. Use values includes recreational use of an area, enjoyment of a scenic view etc. The non-use values are associated with the existence value, i.e. the value of knowing that there is biodiversity or that endangered species are protected.
Contingent valuation is performed in the form of a survey, where people are directly asked about their willingness to pay for a specified marginal change in the quality or quantity of an environmental good. After an average WTP per household per year is determined to get or avoid the specified change in the environmental good, this is multiplied by the affected population to get the annual aggregate social benefit or costs of the affected population.

ii) Choice experiments (CE)

Choice Experiments is also a preference method, which is able to capture both use and non-use value. However, as opposed to Contingent Valuation, people´s preferences for the environmental good is deducted indirectly by asking people to choose between two or three alternatives described by a set of attributes where price is one attribute and aspects of the environmental good(s) in question constitutes the others. The value for each attribute is varied, across the alternatives, and people asked to make repeated choices between them. From their choices, we can then deduct the values people attribute to each attribute (or characteristic) of the environmental good.

B: Revealed Preference Methods

i) Travel cost (TC) method

The TC method is a revealed preference method that can derive only the recreational use value of the current use of a recreational area. People are in surveys asked the number of times they visit a specific area, their travel costs to the area, and questions about other factors which determines their frequency of visits. From this one can deduct their consumer surplus, which is what they maximum are willing to pay, over and above their current annual travel costs to the site, in order to have the recreational experience they now have. This consumer surplus is their annual recreational use value. This can then be divided by the mean number of days annually they come to the site in order to get a recreational use value per activity day. This consumer surplus can also be derived in a simple Contingent Valuation exercise, where we ask the recreationists their maximum annual WTP, over and above their current annual costs, to have the same experience as they had at this particular recreational site. For a database of recreational use values from CV and TC studies, see the "Recreational Use Values

Database" for an overview of average values for different recreational activities in North America: http://recvaluation.forestry.oregonstate.edu/. The TC method builds on a set of strict assumptions, which need to be tested for, and corrections made if the assumptions are not fulfilled (e.g. if people incur the travel costs to the recreational site with also other motivations than recreation like visiting relatives, i.e. multi-purpose trips).

ii) Hedonic Pricing (HP)

Market prices of houses and cabins represent what people are willing to pay for all characteristics of the houses/cabins, and in Hedonic Pricing (HP) we collect data on market prices and all characteristics of the house including environmental attributes like noise level, air level, distance to parks, distance to polluted sites etc. In regression analysis we can then deduct the marginal WTP for the different environmental characteristics. For instance if house prices increase 1 % per 100 meter distance to a contaminated site, this means that a house 1 km away will have a 10% higher value, all other things being equal. The HP method builds on a set of strict assumptions, which need to be tested for, and corrections made if the assumptions are not fulfilled (e.g. if people did not have full information about all characteristics of the house, including environmental qualities, when they bid for the house).

iii) Averting costs (AC)

Costs that people incur to avoid or avert environmental and health impacts, e.g. buying bottled water if the water is contaminated, can be used as a proxy for their WTP to avoid polluted drinking water. In most cases, averting costs would be a lower estimate of their maximum WTP for the environmental or public health impact in question.

iv) Replacement costs

The replacement cost method assumes that an environmental good can be replaced by a human engineered system. For example, the recreational value of a lake that can be decontaminated may be assessed by analysing the price to create and maintain an alternative pond. The costs for this would correspond to the value of the environmental benefit.

The method assumes that the engineered system should provide exactly the same functions as the environmental service, i.e. it would be a perfect substitute.

EXAMPLE
In a study by Hanley et al (2001), the contingent valuation method was used to estimate people's willingness-to-pay (WTP) for risk reduction from contaminated food in Scotland and Norway, following a Chernobyl-type accident. The respondents were presented two choices for the purchase of lamb meat, a treated and an untreated alternative. The former was lamb meat from an area affected by fallout, but treated to reduce radioactivity to below safe levels (in the sense that mitigation options were undertaken to reduce the contamination level). The latter was the same product which had been imported from an area not affected by fallout. The respondents were asked how much more than the average current price they were willing to pay for untreated lamb. The mean WTP was + 29% for the Scottish respondents and +37% for the Norwegian ones.

This difference between people´s WTP for lamb meat from an unaffected area and their WTP for affected lamb meat that had been treated reflects people´s disutility of affected lamb meat even if it is treated. Thus, people´s total disutility of contaminated lamb meat is their WTP to avoid eating this meat and the costs of treating the lamb meat. This disutility aggregated over their total annual consumption of lamb meat (assuming they will not substitute lamb meat with other types of meat or food), and aggregated over all affected households will then be a measure of the social costs of contamination of lamb meat due to the incident.

2.4 Describe non-monetized impacts

Preferably, all impacts should be assigned a monetary value by using market prices or shadow prices. However, there may be cases when this is not possible due to lacking methodology or limited time and resources to perform the analysis. Typical examples could be impacts on environmental quality, cultural heritage, scenery, and biological diversity. These impacts should then be assessed in a qualitative way compared to the *Reference alternative*, preferably according to importance and extents in a consistent and objective way.

One possibility is to use a plus/minus matrix (DFØ, 2018). The first step is to assess the importance of the area to be mitigated for the affected groups or the society as a whole, for instance on a scale low-medium-high. "Importance" here refers to the level of **national** importance. So importance is high if it is important at the national level, e.g. a national park. If the recreational area is of importance to a region, importance is medium, and if it is of importance to a municipality or part of a municipality, it is of low importance. Then to assess the magnitude of impacts for that area for each mitigating option as low-medium-high for both positive and negative impacts. The impact can then be assessed using the impact matrix in Table 1. A finer or coarser scale can also be used, depending on the how detailed information we have about the non-monetized impacts.

Table 1: Impact matrix for non-monetized impacts

Magnitude\Importance	**Low**	**Medium**	**High**
High positive	+/++	++/+++	+++/++++
Medium positive	0/+	++	++/+++
Low positive	0	0/+	+/++
None/negligible	0	0	0
Low negative	0	0/-	-/--
Medium negative	0/-	--	--/---
High negative	-/--	--/---	---/----

Although these qualitative impacts should not be used in the cost-benefit calculation, they should be presented to the decision-makers as part of the CBA results (see 2.8).

2.5 Calculate net present value (NPV) for each mitigating action

In this step, we aggregate annual benefits and costs of the project over the life time of the project by calculating the Net Present Value (NPV) in order to see if the net social benefits of the project is positive (i.e. the present value of the benefits PV(B) exceeds the present value of costs (PV(C)), see the equation below).

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1+r)^t} = PV(B) - PV(C)$$

Where B_t is the annual social benefits in year t, C_t is the annual social costs in year t, r is the social discount rate and T is the time horizon of the project.

The social discount rate r can be seen as a weight that makes cost and benefits in the future comparable to todays' costs and benefits (Boardman et al, 2014), and is in practice politically determined based on assessment by economists. In Norway, for instance, *r* is currently 4 % p.a. (per year) in the CBA guideline from the Ministry of Finance, i.e. r = 0.04, for projects with time horizons up until 40 years. Note that this is a *real* rate of return (i.e. corrected for inflation, whereas e.g. an interest rate offered for your savings by a bank is a nominal rate, where the inflation has to be subtracted to get a real rate of return (e.g. if the bank rate was 3 % p.a. and the inflation rate according to the Consumer price index was 2% p.a. then the real rate of return is 3 minus 2 = 1 % p.a.). When valuing costs and benefits we also present values in real rather than nominal terms (i.e. at a fixed price level, e.g. 2019-€).

It is common that national governments have defined a social discount rate to be used in CBAs of public projects in their country. For the European Union the social discount rates (real rates of return) recommended by the European Commission are 5% for cohesion countries (Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia, Slovenia), and 3% for the other member states (Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Spain, Sweden, United Kingdom) [European Commission, 2014].

2.6 Perform uncertainty analysis

The aim of this step is to analyse how NPV changes when uncertain costs and benefit components change, in order to determine how sensitive NPV is to these changes and at what level of the uncertain component NPV would be zero. Determining how many % NPV change with a 1 % change (positive or negative) in the uncertain benefit and cost component will identify the benefit and cost components which are most critical to whether the project is profitable (i.e. NPV > 0).

For remediation options there could be uncertainties e.g. in the investment cost (e.g. ±15 %), or a possible range in the expected remediation efficiency (e.g. 65-90%).

The sensitivity of NPV from changes in the base case (i.e. the assumptions used to calculate the NPV) of each of the benefit and cost components (as well as the discount rate and time horizon) can be illustrated in "star diagrams" like the one below. Here we can see how NPV (on the y-axis) changes with different percentage changes from the base case of each component (on the x-axis). 0 % on the x-axis shows the NPV in the base case. In the example given in Figure 2 below, the NPV is 5 million €. Steeper curves means NPV is more sensitive to changes from the base case for that particular cost or benefit component (which would be downward and upward sloping, respectively). These diagrams also show the critical value for each component, in terms of where the line crosses the NPV=0 line. This shows the percentage change in this component that will shift the NPV from negative to positive, i.e. shifting the project from profitable to unprofitable, or the other way around. If only a small change in the base case of a component changes the project from profitable to unprofitable (or the opposite), it shows that the project is very sensitive to changes in this benefit or cost component.

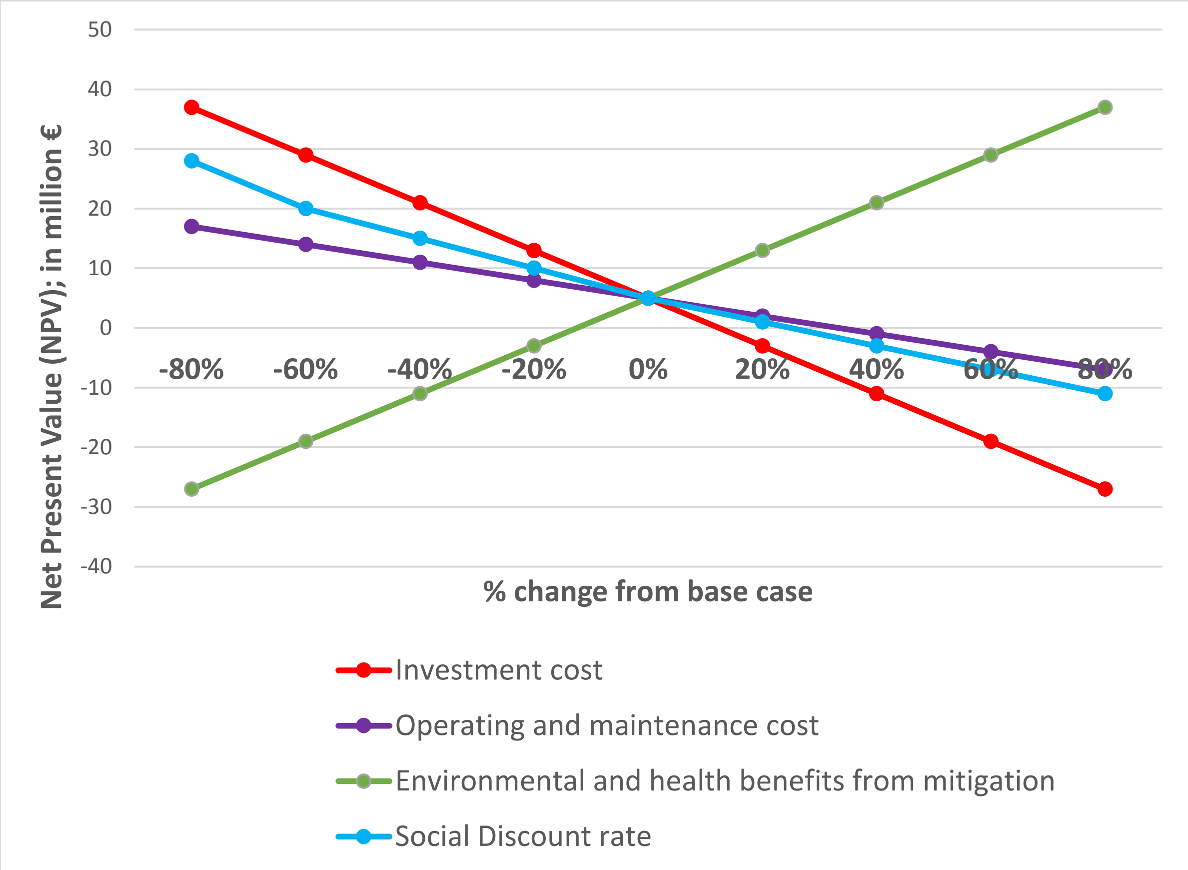

Figure 2: Illustration of a possible % change in NPV from the base case for four different cost and benefit components

Changing one benefit or cost component at a time in these sensitivity analyses does, however, not tell what would happen if more benefit and cost components change at the same time. Scenario analysis achieves this by calculating NPV for each mitigating option by using the most pessimistic (i.e. worst case scenario) and most optimistic (i.e. best case scenario) of the identified uncertain components. If NPV > 0 even in the worst case this is very robust project in terms of socio-economic profitability. The CBA will then get an expected NPV and an NPV range from pessimistic to optimistic for each mitigation option. In principle, every value in the CBA can be varied, but it is wise to use judgement and focus on only the most critical factors, i.e. those that would give the largest deviation from the base case NPV value.

Let's say a mitigating option A has an expected NPV of 20 million €, i.e., a net social benefit of 20 million €. When the implementation cost is varied ±15 %, the pessimistic NPV (using the highest investment cost) would be e.g., 15 million € while the optimistic NPV (using the lowest investment cost) would be 25 million €. The range in NPV would thus be 15 to 25 million € with an expected NPV of 20 (if there is a 50% probability of both 15 and 25 million €). In any case, the option would still have a net social benefit and be profitable.

Let's say a mitigation option B has an expected NPV of 5 million €. The expected value for remediation efficiency is 85 %. If a pessimistic value is chosen (e.g., 65 % = lowest efficiency), the NPV will be -2 million €. If an optimistic value is chosen (e.g., 90 % = highest efficiency), the NPV will be 6.75 million €. The range in NPV would thus be -2 to 6.75 million € with an expected NPV of 5. We see here that the NPV will actually be negative for the pessimistic value meaning that the option has a net social cost instead of a benefit.

For each critical uncertainty factor, the same procedure should be repeated, one by one. This is also called a partial sensitivity analysis. The analyst can also choose to go further and consider worst- and best-case analyses where the aim is to establish if a combination of reasonable assumptions would reverse the NPV from positive to negative (Boardman et al, 2014).

The uncertainty analysis is particularly valuable in situations where two mitigating options might display the same expected costs and benefits, but where the uncertainty of the costs and benefits is much larger for only one of them.

The range of NPVs from pessimistic to optimistic should be presented to the decision-makers for each mitigating option together with the expected NPV and the non-monetized impacts (see chapter 2.8). If many ranges have been calculated, only the most important ones should be presented to the decision-makers. These will often be the ones with a higher risk of significant lower net social benefit in the pessimistic assessment.

Also the non-monetized impacts can be analysed for their uncertainty, yet in a qualitative, descriptive way.

2.7 Describe distributional effects

The option(s) that are chosen may have a net social benefit, but the effects may vary between different interest groups and geographical areas. One interest group may benefit greatly from the implementation of a mitigating option while another may experience losses. How the cost and benefits are distributed among different groups, is called the distributional effects. The description of distributional effects is not a part of the ranking of possible options, but should be presented to decision makers as they could be interested both in the economic efficiency (i.e. the options with the highest NPV) and equity (i.e. the distribution of social costs and benefits on the different interest groups).

Such distributional effects might be seen in e.g. low vs high income households, urban vs rural households, or households directly affected by remediation options that benefit from clean-up vs all households in the country paying for the remediation through taxes (if remediation is paid by public funds).

If an option has a significant negative impact only on certain interest groups or geographical areas it should be considered if, and how, these groupings should be compensated. Note, however, that the theoretical underpinnings of CBA (i.e. the Kaldor-Hicks criterion or Potential Pareto-improvement) only says that a project is profitable if the social benefits exceed the social costs and winners **can** compensate losers. Thus, compensation does not have to take place for the project to pass the Benefit-Cost test (i.e. NPV>0).

2.8 Make a recommendation

This final step in the CBA is to prepare an overall assessment of the options relative to the *Reference alternative*. The assessment should include the calculated NPV, the non-monetized impacts (if any) and the uncertainty analysis. Based on this a ranking of the different options should be presented as a recommendation to the decision-makers. Considering only the monetized impacts, if project options are mutually exclusive and independent and there are no constraints on costs, the option with the highest positive NPV should be chosen. If all costs are constrained in terms of a budget, the

Benefit/Cost (B/C) ratio (e.g. Present Value of Benefits divided by the Present Value of costs) should be used, and should be higher than 1. E.g. if the B/C-ratio is 2, it means that for every euro of costs from the constrained budget we get a benefit of 2 euro. If only parts of the costs (e.g. the investment costs) comes from a constrained budget the Present Value of net benefits (B-C) should be divided by the constrained part of the costs (Cc), and the (B-C)/Cc –ratio should be higher than 0. However, the non-monetized impacts and the results of the uncertainty analysis should also be considered in addition to these monetized costs, when the ranking of projects is made. Distributional effects should then be presented, enabling the decision makers to evaluate not only economic efficiency but also equity of the different project alternatives/options.

To allow for transparency and verification of the results the analyst should document all assumptions, data sources and methods used in the CBA in the report. When presenting the results to the decision-makers, however, it would be most useful to present a more condensed summary of the main results and the assessment used to rank the various options. Table 2 gives an example of how such a recommended ranking could be presented.

Table 2: Overall assessment and ranking of three different mitigating options

CBA elements	Option A	Option B	Option C
Monetized impacts			
Benefits	352	31	202
Costs	10	9	18
I. Calculated net present value (NPV)	342	22	183
Non-monetized impacts			
Benefits			
Improved environmental quality	++/+++	0/+	++
Preserved biodiversity	+/++	0/+	0/+
Costs			
Damage to scenery	--/---	0	0/-
II. Overall assessment of non-monetized impacts (ranking)	1	2	2
Ranking based on net social benefit (from I and II)	1	3	2
Uncertainty	Interval:	Interval:	Interval:
Monetized impacts (pessimistic-optimistic)	-50 to 705	-4 to 60	-45 to 393
Non-monetized impacts (qualitative assessment)	medium	small	small/medium
III. Overall assessment of uncertainty	medium	small	medium
Ranking based om overall assessment of I, II and III	1	3	2

3. Application of the CBA framework to the Huelva NORM site in Spain

Disclaimer: We have used the Huelva NORM site to illustrate how the CBA framework can be applied to a radioactively contaminated site. We have not been commissioned by Spanish authorities or other actors to perform a CBA. The following chapter is for illustrative purposes only and will not be used in the ongoing decisions about remediation work on the actual site. We have used available information to the best of our knowledge, but not conducted any specific studies related to the site. The conclusions of the CBA are for illustrative purposes only and must not be taken as a recommendation to the Spanish government or any other entity or stakeholder.

3.1 Project definition

Phosphate fertilizer production facilities are one of the industries known to produce large amounts of waste and/or by-products containing naturally occurring radioactive materials (NORM) that can have a negative impact on health and the environment due to radiation exposure. In many cases, there will also be a potential chemical risk associated with the handling and storage of this waste or by-product.

The phosphate minerals existing in nature are not suitable to be directly used by plants. To make it consumable by a plant via root uptake, phosphate ore is processed into phosphoric acid, which is further used in the production of fertilizers. As a side effect, phosphogypsum is often produced which can be treated as a by-product or a waste material and which must be handled accordingly. The natural radionuclide content in the raw phosphates can be relatively high compared to background levels, for instance UNSCEAR reports an average of 1500 Bq/kg for ^{238}U (UNSCEAR, 1993) content in the phosphate ore, which makes the material potentially radiologically hazardous according to Council Directive 2013/59/Euratom of 5 December 2013, hereafter referred to as "BSS" in this report (Official Journal of the European Union, 2014).Depending on the type of the process and the acids used, the radionuclide content in the residues can either be diluted or enriched.

3.1.1 Huelva site description

The storage site in the industrial area of Huelva, Spain has been actively used for phosphogypsum deposition between 1968 and 2010. The site used to accumulate up to 3 million tons of the industrial residues annually (Gitzinger et al, 2009) coming from two industrial companies. Today, new onsite storing of the residue streams has stopped, however, the total phosphogypsum mass in the storage area is estimated to be around 120 million tons. The presence of harmful chemicals and elevated radionuclide concentrations in these residues has created a concern that it might be a potential hazard for the nearby population, the workers, and the environment. It was reported that the activity of these residues in the two storage ponds is around 490 - 650 Bq/kg for ^{226}Ra and 30 for ^{232}Th (Cost network NORM4Building, 2017), (Dueñas et al, 2010). Even if the activity concentration is below the exemption level (1 kBq/kg) for moderate amounts of material in the EU BSS, the total amount of Ra-266 significantly exceeds the total activity exemption level of 10 000 Bq given in ANNEX VII, Table B, column 3, of the EU BSS (Official Journal of the European Union, 2014). It is stated that “The values laid down in Table B, column 3, apply to the total inventory of radioactive substances held by a person or undertaking as part of a specific practice at any point in time.”

The storage site is located south-east of the Huelva city (Figure 3) that is inhabited by approximately 144 000 people. The storage site presents social and environmental safety concerns for the local population. The local population is worried about potential leakages of radiologically and chemically hazardous elements from the storage site, about quality of air and water in the region, and about potential impacts on their health. Figure 3 also shows the overview of the whole area (covering 12 km^2): Zone 1 has been partially restored by covering with 25 cm of soil and new vegetation, Zone 4 is un-restored, and Zones 2 and 3 corresponds to the storage ponds for the phosphogypsum stacks. To the west of Zone 1, the industrial production and complexes are still operational.

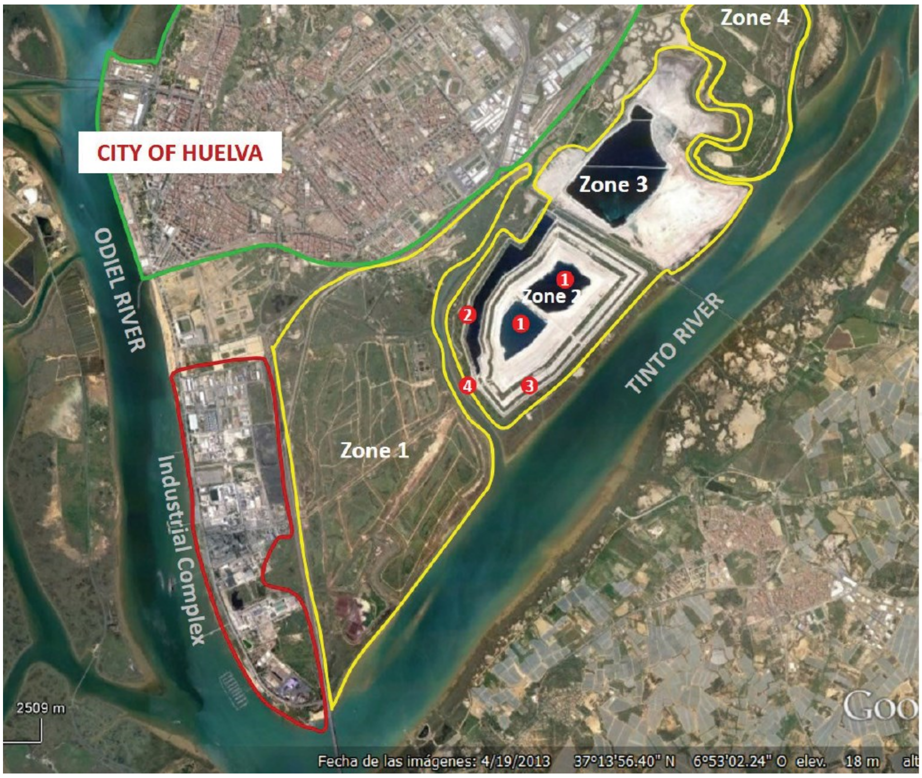

Figure 3. Aerial photograph of the area of the Tinto river marshes. (1) Settling ponds, dumping area of phosphogypsum; (2) regulating reservoir, (3) perimeter channel, and (4) pumping station. Source: (Guerrero-Márquez et al., 2017)

Investigations undertaken by the University of Malaga (Dueñas et al., 2010) in the four different zones showed that only levels of ^{226}Ra is substantially enriched above natural levels, in the range 520-740 Bq/kg in unrestored zones. Much lower values of ^{226}Ra were found in the restored zone: 17-210 Bq/kg. An Environmental Protection Agency ruling prohibits phosphogypsum with levels of ^{226}Ra above 370 Bq kg^{-1} to be applied to agricultural soils. The estimated maximum individual doses for workers on the site was estimated to 0.335 mSv/y by Dueñas et al. (2010).

3.1.2 Goals of the site remediation

To reduce potential radiological and chemical burdens on the local population and environment, there is an ongoing investigation of possible site remediation options. Three different site remediation alternatives have been suggested by experts; these alternatives are described below as “Project alternative A: in-situ storage”, “Project alternative B: ex-situ storage” and “Project alternative C: combined approach.” For radiological exposure, the remediation goal is defined as doses caused by the site to members of the public to be lower than 0.1 mSv per year. In addition, there is a goal to restore the site to a natural landscape marsh area, or as a recreational area for the citizens of Huelva (and beyond).

In the current study we aim to perform cost-benefit analysis of these remediation options and compare them with a “Do nothing” option, where no actions are taken (also termed the Reference alternative). The time horizon of these scenarios is set to 50 years, which corresponds to the planned time of the phosphorous industry to continue operation in this area plus an additional 10 years. It is expected that the industry would be financing the remediation project.

3.1.3 Description of the reference alternative and three project alternatives

Reference alternative (or the “do nothing” option). This scenario assumes that no additional actions are taken to reduce potential chemical and radiological exposure to the public and the environment, and that the site remains as it is with two zones filled with phosphogypsum. It is assumed that the industrial plant operation would remain unchanged, although no new storage of phosphogypsum on the site will occur.

Project alternative A – in-situ storage. Protective barriers would be introduced in the two storage zones (Zones 2 and 3) to reduce the transfer of radionuclides and chemicals to the environment. The whole site (zones 1-4) would be covered with a layer of soil and revegetated, and environmental monitoring of the site will take place. Such an area would after remediation be fit for recreational purposes and could be seen as an urban park area conveniently located for residents of the city of Huelva and the municipality of Huelva. The implementation period would be 10 years to fulfill the remediation.

Project alternative B – ex-situ storage. In this approach, all the waste would be removed and stored offsite in landfills. It is assumed that the waste would be categorized according to its hazard potential and stored in different waste landfills according to hazard category. It is estimated that 10 new landfills would need to be constructed to accommodate all this waste. Furthermore, it would take 30 years to finish the remediation and transfer all the material to the new landfill sites (EGMASA, Empresa de Gestión Ambiental, 2010). The landfills will then be closed and the areas revegetated.

The area itself would with time return to a natural marshland to the benefit of flora and fauna in the area. There will be no need for post-remediation environmental monitoring of the site.

Project alternative C – combined approach. Here, a combined approach towards the site remediation would be applied. Waste would be excavated and processed on-site. 20 % of it would be stored on-site, while the most hazardous fractions (50 %) would be removed and stored off-site in new landfills. 30 % of the phosphogypsum would be sold and re-used in the production of building materials, for road construction or for soil amendment (García-Tenorio, Bolivar, Gazquez, & Mantero, 2015). We assume that the implementation will take 15 years in total.

Half of the site will be covered with soil and revegetated, while the other half will be returned to natural marshland. There will be no need for post-remediation environmental monitoring of the site.

3.1.4 Stakeholders

There are five clear stakeholder groups related to remediation of the Huelva site.

First, the phosphate industry represented by the companies on site. They have an economic interest in continuing the production at the site to make profit. The current production is 250 000 tons per year of phosphoric acid, ammonium phosphates, and complex fertilizers. At the same time, they have been subject to stricter regulations by authorities over the latest years and are not allowed to discharge contaminated water to the rivers Odiel and Tinto anymore. They are no longer producing phosphogypsum, but instead importing phosphoric acid directly from Morocco. So no new waste is being stockpiled at the Huelva site. However, the legacy waste piles must be handled in a satisfactory way. Remediation of the waste ponds will have direct costs related to the implementation and follow-up.

Secondly, the workers involved in the site remediation. They would be exposed to chemical and radiological risks when operating on the storage ponds. For remediation work, their exposures will increase during implementation.

A third stakeholder group is the citizens of the city of Huelva who live close to the site (neighbours). Citizens are worried about health and safety, chemical and radiological risk, air quality and contamination of soils and water in their local environment. They fear that the site is a risk to their health and well-being. There is concern over the possible emission of radioactive substances to soil, water and air affecting human health, and effluents from the waste storage ponds into the environment that will pollute the habitats of various flora and fauna. Some also express concern over the tectonic stability of the site due to the vast amount of waste stored there (TERRITORIES Deliverable report 9.67, 2019). The may also be negatively impacted during remediation work due to increased noise and air pollution (from excavation and from transportation of material away from the site).

The fourth stakeholder group is the regional population in the municipality of Huelva and Andalusia region. They may have an interest in the health and environmental impacts of the waste ponds on the surrounding areas, even if they are not directly affected. They may have an interest in preventing environmental damage to species at the site and surrounding areas, and the safe recreational use of the surrounding area, e.g., driving boats, fishing and swimming in the rivers Odiel and Tinto. During a possible remediation of the site, these people will be affected by the transportation of waste material away from the site for disposal in new landfills, since the transportation routes will be across Andalusia (and possibly beyond). New landfills may be constructed in Andalusia or in other regions.

The fifth stakeholder group is the public in general including the regional and national authorities (represents all tax payers). The authorities would have to control that remediation work is performed as planned and, depending on project alternative, perform emission and environmental monitoring at a level above or below todays monitoring as in the Reference Alternative.

Please note that one person can be part of several stakeholder groups.

There is at present a large controversy over the production site, the waste ponds and the future remediation of the site. Irreconcilable interests for the land use (industrial versus tourism and recreation) is one important cause of the controversy. Some accuse environmental organizations of creating unnecessary alarm among tourists. Another reported reason for controversy is the unclear division of roles and responsibilities of various local, regional and national authorities (TERRITORIES deliverable report 9.67, 2019).

3.2 Description and quantification of impacts

The area to be remediated is 12 km^2. The two ponds contain 120 million tons of phosphogypsum. An environmental monitoring program is in place for the Reference alternative.

3.2.1 Impacts for the industry

Project alternative A – In-situ

Costs related to confinement of leaching, reconditioning, covering with soil, and re-vegetation. Post-remediation monitoring as in the Reference alternative.

Benefits – none.

Project alternative B – Ex-situ

Costs related to excavation of material, transportation and final disposal. 10 new landfills must be constructed, and material should be divided into different categories based on its level of hazard to store in different disposal sites. The costs include additional monitoring and measurements to gather more data on the residue activity.

Benefits: No post-remediation monitoring is needed which is a benefit compared to the Reference alternative.

Project alternative C – Combined approach

Costs: Material would be divided based on its hazard potential into three categories and this would imply investigation costs like the alternative B. Next, we assume, that 50% of the material would be relocated to storage sites in the same manner as in the alternative B, 30% material would be reused by the construction industry and the remaining 20% with the lowest activity would be treated in a similar way as in the alternative A. Similar treatment to other alternatives would result in the cost proportional to these alternatives.

Benefits: It is also assumed that the residue remaining at the storage site would be of low activity, comparable to the environmental levels and therefore no post-remediation environmental monitoring is needed. Benefit also come from the use of phosphogypsum in other products, i.e., income from selling the material.

3.2.2 Impacts for the workers

The impacts for the workers would be similar for all three Project alternatives and would result in elevated radiological exposure during remediation work. It was estimated by Dueñas et al. (2010), that the full-time worker at the phosphogypsum piles would receive a total excess exposure up to 0.293 mSv per year. We do not include any consideration of the workers needed for other purposes that do not come into contact with the phosphogypsum, since their doses will be negligible.

Project alternative A – In-situ

It is assumed in the current analysis, that 50 full time employees working on the storage site would be enough to complete the project, resulting in a collective effective dose for all workers over 10 years of 0.168 manSv. The work would include covering the area with the layer of soil, as well as installation of protective barriers. The last 30 years of the Project period there would be no further exposure.

Project alternative B – Ex-situ

It is assumed that 100 full time employees would be required to excavate, sort, carry and load all the residue material at trucks aimed for the new repositories. This would result in a collective effective dose for all workers over 30 years of 1.005 manSv.

Workers involved in the construction of the repositories would not be in contact with phosphogypsum and therefore would not be exposed. They are not included in the calculations.

Project alternative C – Combined approach

In this alternative it is expected that 50 % of the material would be excavated and relocated to landfills, while 30% of the phosphogypsum would be used by the construction industry in the landfills or in the brick production. It is assumed that the phosphogypsum would be mixed with other components to prepare material mixtures for sale and therefore the radionuclide content would be diluted levels where it would not pose elevated radiological exposure to workers who handle it after buying. It is assumed that 70 full time employees would be enough to complete all the work related to alternative C. This would result in a collective effective dose for all workers over 15 years of 0.352 manSv.

3.2.3 Impacts for the neighbours

There are 144,258 inhabitants in the city of Huelva, and approximately 54 437 households based on 2,65 inhabitants per household in the municipality statistics. According to (Gitzinger et al., 2009) "*The radiological impact on the public, caused by phosphogypsum piles can also be evaluated as negligible or nil. The values of external irradiation dose rates and the concentrations of ^{222}Rn in the city of Huelva correspond to background values.*" This is based on an assumption that the citizens today are not spending any time on the storage sites, and that any emissions to air are rapidly diluted so that exposures in the city of Huelva are negligible. Even if this has been communicated to the public, they do not fully trust this and the worry related to health and safety persists.

Project alternative A – In-situ

Benefits are related to a more beautiful scenery and that the site can be used for recreational purposes. We can assume the remediated site will take the value of an urban park with several benefits for the citizens of Huelva City, such as leisure, sport and recreation, as well as habitats for various species, local climate regulation, and aesthetics (Bokarjova et al, 2018; del Saz Salazar and Menedez, 2007).

Effluents from the site are stopped, i.e. less negative health and environmental impacts.

The contamination is not removed, so some worry will remain, but less than in the Reference alternative (partial public reassurance).

Costs – none.

Project alternative B – Ex-situ

Benefits related to the fact that all contamination is removed, i.e. no health and environmental impacts anymore. Since all the waste is removed, we must assume that the public is fully reassured of the safety of the site.

The land will in time return to a natural marshland that can be inhabited by various flora and fauna. The scenery will be more beautiful than in the Reference alternative, yet the citizens will not use it as an urban park like they would with option A.

Costs: Negative impact due to increased noise and air pollution during remediation and transportation of material away from the site.

Project alternative C – Combined approach

The benefits will be somewhere between Option A and B related to the public reassurance of reduced impact on health and environment. Additional benefits from transforming the site into partly an urban park and partly marshland.

Costs: Negative impact due to increased noise and pollution during remediation and transportation of material away from the site.

3.2.4 Impacts for the regional public

In the municipality of Huelva there are 196 000 household of which around 54 437 households are within the city itself. The region Andalucía has approximately 8,3 million people.

Project alternative A – In-situ

Benefit related to the creation of an urban park in the area and less contamination of the environment.

Costs – none.

Project alternative B – Ex-situ

Benefit related to the knowledge that there is no contamination of the environment. Benefit from the change from industrial site to a natural marshland to be used by flora and fauna.

Since all the waste is removed, we must assume that the public is fully reassured of the safety of the site.

Costs related to the noise and air pollution from transport of the waste from the site to waste landfills. Possible construction of new landfills in the Andalusia region.

Project alternative C – Combined approach

Benefits related to the remediation of the area as partially an urban park and partially a natural marshland, and less contamination of the environment.

Costs related to the noise and air pollution from transport of the waste from the site to a waste landfill and possible construction of new landfills in the Andalusia region, but less than in project alternative B.

3.2.5 Impacts for the public at large (including authorities)

Project alternative A – in-situ

Benefits: less time needed by authorities for surveillance of the site and effluents and addressing public worries. New urban park created that can be used also by tourists.

Cost of remediation work, if (part of) it is to be paid by tax money.

Project alternative B – ex-situ

Benefit: No post-remediation surveillance needed and no emissions to the environment. Return of the area to natural marshland as a habitat for various species and no effluents to the environment.

Cost of remediation work and construction of new landfills, if (part of) it is to be paid by tax money.

Project alternative C – combined approach

Benefits: No post-remediation surveillance needed and no emissions to the environment. Partial new urban park created that can be used also by tourists, partial return to natural marshland as a habitat for various species.

Cost of remediation work and construction of new landfills, if (part of) it is to be paid by tax money.

3.3 Monetizing all impacts

3.3.1 Valuing impacts using market prices

Project alternative A – in situ.

Costs: Investment costs have been estimated to be 70 million EUR in 10 years and would be paid by the industry. Post-remediation surveillance and monitoring costs are assumed to be similar to the reference alternative and therefore not considered as costs or benefits.

Benefits: None that can be characterized with market prices.

Project alternative B – ex-situ.

Costs: The estimated implementation cost would be 2 830 million EUR (EGMASA, Empresa de Gestión Ambiental, 2010) and would result in the transfer of roughly 100 million tons of residue to 10 new landfills that would need to be constructed for the final storage. This would also include costs associated with the investigation to separate phosphogypsum based on its activity concentration and the costs to maintain and operate landfills until their closure after 30 years. After closure, the areas will be revegetated. An example of calculation of cost for implementation is given in Table 3. Environmental monitoring costs after closure of the landfills are not included in the analysis.

The phosphogypsum would be separated into hazardous and non-hazardous fractions and it was previously estimated that the associated cost for every fraction would be roughly equal (EGMASA, Empresa de Gestión Ambiental, 2010) thus we further assume that fractions of hazardous and non-hazardous material are also equal in terms of cost.

Benefits: No post-remediation monitoring would be needed, the estimated benefit is 50 000 EUR annually in saved monitoring costs.

Project alternative C – combined approach.

Costs: The hazardous fraction (50% of the material) would be excavated and removed from the site to 5 new landfills that will be constructed. The costs are considered to be proportional to the ones in alternative B and would amount to 1 415 million EUR. We also here assume, that these costs would cover survey to partition residue based on its activity concentration.

20% of the material would remain on the site and this part of the cost would be proportional to alternative A, reaching 14 million EUR.

The total cost will thus be 1 429 million EUR.

Benefits: No post-remediation monitoring would be needed, the estimated benefit is 50 000 EUR annually in saved monitoring costs.

The income from selling the phosphogypsum for other purposes such as the construction industry or other is estimated to be roughly 17.5 EUR per ton (in 2019-prices) based on the current price of phosphogypsum sold in Brazil. This would result in a combined benefit (if 30% of the phosphogypsum is sold on the market) of 630 million EUR, under the assumption that there is perfect competition in this market.

Table 3: Estimated implementation costs for Alternative B – ex-situ; in EUR (EGMASA, 2010) and corresponding values in 2019 EUR calculated with the Consumer Price Index (CPI) of Spain (https://www.ine.es/calcula)

Cost item	Million EUR total 2010	Costs incurring in year(s)	Million EUR/y 2010	Million EUR/y 2019
Excavation of material	1 046,65	0-29	34,89	38,90
Transportation	754,03	5-29	30,16	33,63
Construction of 10 landfills	311,11	0-4	62,22	69,38
Operation of landfills	278,18	5-29	11,13	12,41
Closure of landfills	141,24	30	141,24	157,48
Revegation of landfill sites	7,28	30	7,28	8,12

3.3.2 Valuing impacts without market prices

Radiation exposure to workers

The ICRP has defined the concept of collective effective dose where exposures are summed over a number of individuals for a group over a given time period. They state specifically that this term is to be used for optimisation of protection measures only and not for calculating projected deaths in a given population that receive very low doses over a prolonged time period. “The collective effective dose has been and remains a key parameter for optimisation of protection of workers” (ICRP, 2007). In our case, the calculated excess risk from collective effective worker doses can be used to evaluate the negative impact from the exposure for the different Project Alternatives. We relate the excess risk of cancer death from radiation exposure to the Value of a Statistical Life (VSL) so that the negative impact from radiation exposure can be expressed in monetary terms comparable to other monetized impacts. We do this for optimisation purposes only (being one element in the comparison between different Project Alternatives) and under no circumstance are we claiming that this is appropriate for projecting the number of possible deaths among the workers in our case study.

The collective effective doses to workers during remediation is estimated to 0.168, 1.005 and 0.352 manSv for alternatives A, B and C, respectively. According to ICRP, the risk for radiation induced lethal cancer is 0.041 per Sv for adult workers. The number of fatal cancers would thus be 0.007, 0.041 and 0.014 for alternatives A, B and C, respectively. We can monetize the negative impact from the radiation exposure by multiplying these values with the VSL. The OECD (2012) recommended a value of 3 600 000 USD for the European Union (from a meta-analysis of stated preference studies of VSL (Lindhjem and Navrud, 2015; Lindhjem et al, 2011)). This value is converted into EUR using the Purchasing Power Parities[1] for Spain, published on the OECD website (https://stats.oecd.org/index.aspx?DataSetCode=SNA_Table4) resulting in 2 501 914 EUR (in 2012 value). Using the Consumer Price Index of Spain, this converts into 2 642 021 EUR (in 2019 value). The cost of the increased cancer risk is thus 18 144, 108 864 and 38 103 EUR for alternatives A, B and C, respectively. These values can be divided over the number of years of exposure in each alternative to obtain annual costs that can be discounted in step 5 like any other cost.

[1] Purchase Power Parity (PPPs) are the rates of currency conversion that equalize the purchasing power of different currencies by eliminating the differences in price levels between countries. For more details, see http://www.oecd.org/sdd/purchasingpowerparities-frequentlyaskedquestionsfaqs.htm

Potential benefits

The project alternatives will convert the storage ponds to an urban park (alternative A – in situ), a natural marshland (alternative B – ex-situ), or to a combination of partial urban park and partial marshland (alternative C – combined approach). We could estimate the welfare improvement to people in Huelva and in the region of theses project alternatives by conducting a new Stated Preference survey of their willingness-to-pay (WTP) to get theses environmental improvements (compared to the reference alternative). This would give the most accurate value for the Huelva site.

Such primary valuation studies are, however, time and resource consuming beyond what is available in the TERRITORIES project. The alternative is to use value transfer /benefit transfer (Navrud and Ready 2007), where we transfer results from previous non-market valuation studies at other sites that could be considered comparable in terms of the environmental good (and change in quality/quantity) valued.

del Saz Salazar and Menédez (2007) performed a Contingent Valuation (CV) study of 900 randomly chosen inhabitants of Valencia in Spain to estimate the non-market benefits of creating an urban park in Valencia. The former central train station area was to be transformed into an urban park. In the CV study, households in the 5 nearest districts and 14 less affected districts were asked how much they were willing to pay annually in additional tax the next 5 years for the creation of the park. Since WTP was larger for the areas closest to the site, they calculated a weighted mean value for the households in Valencia of 8920 Pesetas/household/year. The study was performed in 2001 before the € was introduced. 8920 Pesetas corresponded to 53.61 €[2] in 2001. The GDP per capita in Valencia was 18 749 € in 2001 according to the Spanish regional accounts, and 14 923 € in Huelva. We can then perform unit value transfer with income correction by multiplying the WTP estimate in Valencia with the ratio of GDP (Huelva/Valencia) (assuming an income elasticity of WTP equal to 1, i.e. the WTP changes linearly with the GDP per capita) to find WTP in Huelva in 2001 equal to 42.70 €. By using the consumer price index calculator of the Spanish National Statistics Institute (https://www.ine.es/calcula/) this sum corresponds to 60.65 € in 2019.

We can then multiply 60.65 € with the 54 437 households in Huelva city to reach a sum of 3 301 604 € per year. This annual value represents the social benefits of the urban park to the people of Huelva city. It could be argued that the park would benefit all the 196 000 household of Huelva municipality, and thus the benefits should be aggregated over all of them. If we assume that all the households in the municipality have the same WTP, then the total value of the urban park is 11 887 400 € per year. It should be noted, though, that the benefit of having an urban park will extend beyond the 5 years that the households contribute with extra taxes. del Saz Salazar and Menédez (2007) stated in their WTP-question that the taxation would last for 5 years during which the park would be constructed. This kind of time-limited tax is often used in stated preference scenarios in order to establish a realistic annual value (and avoid protest zero responses from people that are afraid that this will be a tax to be paid forever). Thus, even if the payment is limited in time, we can interpret this as an annual value of a park for the life time of the project. If we only use the annual value for the first 5 years after the park is established, we would therefore probably underestimate the social benefits.

A recent study by Bockarjova et al (2018) presented a meta-analysis of valuation studies using stated preference methods (i.e. Contingent Valuation (CV) and Choice Experiments (CE)) to value green and blue urban nature in a variety of contexts. Their database contained 60 studies with 147 observations, of which 20 studies with 81 observations were from Europe. All WTP estimates were converted into 2016-US dollars per hectare nature area per year. They found that parks are the most highly valued

"[2] The exchange rate between Pesetas and € is 166.386

type of urban nature. They found that the WTP is positively correlated with income (in terms of GDP per capita) and population density, while the regression coefficient of "area" is negative meaning that the value per hectare decrease with increasing size of the nature areas. They also found that the WTP is lower if tax is used as a payment vehicle compared to other payment mechanisms such as an entry fee or a donation to a fund. For the European observations, they found that the choice experiment method resulted in higher WTP values than the contingent valuation method.

From the European data, they estimated a WTP of $ 12 338 per hectare per year. The Huelva site is 1200 ha, which then gives a total WTP of $ 14 805 600 per year (measured in 2016 USD) if the whole site is transformed into an urban park. This corresponds to 9 705 174 € per year when using the OECD Purchase Power Parity corrected exchange rates in 2016 to convert 2016 USD to 2016 €: https://stats.oecd.org/index.aspx?DataSetCode=SNA_Table4 . This is simple unit value transfer without income adjustment. Using the Spanish CPI calculator converts this into 10 190 432 €/y in 2019 €. This value is quite comparable to the unit value transfer with income adjustment for the Valencia case which was 11 887 400 €/y.

Bockarjova et al (2018) also derived value transfer functions both for the global data and for the European data. For the latter, the function takes the form:

Value of nature per hectare per year = exp(7.899 -0.941 ×(ln(Area)-ln(472)) + 1.479×(ln(GDP)-ln(28007))+ 0.205×(ln(population density)-ln(211)) – 3.414×Tax + 3.941×Choice experiment + 2.533×Park + 0.976×Green connected to grey + 0.077× Blue)

Regional data can then be used for GDP per capita and population density and the actual size of the nature area can be inserted. The other variables are dichotomous; taking the value of 1 if "yes" and 0 if "no". By inserting the correct data for the actual site, the value of the nature area per ha per year can be calculated.

Lindhjem and Navrud (2008) found when comparing different value transfer techniques for stated preference studies of use and non-use values of forest areas, that unit value transfer could perform just as well or even better than international meta-analysis. Thus, we suggest using the results from Valencia for the unit value transfer exercise her, since this was a study performed in Spain and where the goal of the project was to establish an urban park, and thus most similar to our study site in Huelva.

For option A, the value of the urban park (once established) is 11 887 400 €/y in present value.

For the natural marshland, a similar value transfer exercise can be performed. Searching the Environmental Valuation Reference Inventory (www.evri.ca) a study by Brenner et al (2010) was found investigating the non-market value of ecosystem services along the Catalan coast in Spain. 14 different non-consumptive services provided by natural and seminatural coastal ecosystems were valued; some of which were not applicable for the Huelva case (e.g. water supply) while 4 of them were appropriate (gas/climate regulation, habitat/refugia, aesthetic & recreation, cultural & spiritual). For freshwater wetlands (which we here assume is similar to marshland) these four ecosystem services had a total value of 6 283 USD (2004 value) per ha per year. This corresponds to 6245.74 € (2019 value) per ha per year (using PPPs for 2004 and the CPI of Spain from 2004 to 2019). The site is 1200 ha. Thus, the total value of the site when restored to natural marshland is 7 494 888 €/y. This would be the value of the remediated site in project alternative B where the whole site will be transformed into a natural marshland.

In project alternative C, half the site will be transformed into an urban park of value 5 943 700 €/y and half the site will be transformed into natural marshland with the value 3 747 444 €/y. The combined value is 9 691 144 €/y. But in this case we need to take into consideration that the remediation into urban park and marshland, respectively, may have different time frames. Project alternative A is estimated to take 10 years to complete while alternative B is estimated to take 30 years. Project alternative C might have different time frames for the urban park remediation and the marshland remediation, as well as having a total completion time less than 30 years. The benefit (in terms of value of the park or marshland) will not occur until the transformation into the park or marshland is finished. This is taken into account in the chapter on calculating the net present values.

3.4 Non-monetized impacts

In the study presented in TERRITORIES Deliverable report D9.67 (2019), stakeholder panel meetings were arranged for Huelva where the three different remediation alternatives were discussed. It revealed that the highest worries among stakeholders were health and safety, radiological risk, and air quality and soils pollution, in that order.

Some of the impacts from performing remediation were not possible to monetize due to lack of data and time constraint for our analysis:

- Reduced environmental impact (less emissions from the site to air, soil and the aquatic environment)
- Reduced worriedness of the population
- Increased noise and air pollution for neighbours and for people living alongside transportation routes and near the final landfills to be constructed

Instead, we do a qualitative assessment of the importance of the area (low-medium-high) and the magnitude of the impacts (from high negative to high positive) for each project alternative, using the matrix in Table 1. “Importance” here refers to the level of **national** importance. So importance is high if it is important at the national level, e.g. a national park. If the recreational area is of importance to a region, importance is medium, and if it is of importance to a municipality or part of a municipality, it is of low importance. For the Huelva case, the importance is thus rated low for reduced environmental impact and public worriedness.

Table 4: Matrix for assessing non-monetized impacts.

Magnitude\Importance	**Low**	**Medium**	**High**
High positive	+/++	++/+++	+++/++++
Medium positive	0/+	++	++/+++
Low positive	0	0/+	+/++
None/negligible	0	0	0
Low negative	0	0/-	-/--
Medium negative	0/-	--	--/---
High negative	-/--	--/---	---/----

For alternative A, the environmental impact will be reduced, and also the worriedness, but to a lesser extent than in alternative B where all the radioactive material is removed. The benefits for option C will be between alternatives A and B.

There will be increased noise and air pollution for the neighbours while the remediation takes place, in increasing order from alternative A to C to B. For alternatives B and C, material will be transported from the site to new, constructed landfills at an average distance of 100 km according to (EGMASA, Empresa de Gestión Ambiental, 2010). This means that the population of Andalusia will be negatively impacted due to the transport and construction of new landfills.

Table 5: Non-monetized impacts assessed for the Huelva site

Non-monetized impacts	**Alternative A**	**Alternative B**	**Alternative C**
Benefits			
Reduced environmental impact	0	+/++	0/+
Reduced worriedness (health and safety)	0	+/++	0/+
Costs			
Increased noise and air pollution	0	-/--	0/-

3.5 Net present values (NPV) for each mitigating action

We have now established the annual social costs and annual social benefits in the present value (stated in 2019 EUR) for all the three Project Alternatives. Then we calculate the annual social net benefits by subtracting the costs from the benefits for each year. The annual results are then discounted by a factor $1/(1-r)^t$ where *r* is the social discount rate per year (in our case 3% p.a.) and *t* is the year the costs and benefits accrue (starting from 2019 as year 0; t=0). We then get the present value of net benefits for each year, which is summed over the time horizon (here the time horizon *T* = 40 years; from year 0 to year 39) to give us the total Net Present Value (NPV) for each Project Alternative. Examples of the calculations are given in Appendix A. Here, we provide the calculated NPVs and a brief comparison and discussion of the obtained results.

Alternative A

In 40 years the NPV was estimated to be **117 million EUR**. The positive NPV is explained by the small investment costs compared to the considerable benefits resulting from the urban park created.

Alternative B

Very high investment costs over a long time period (30 y) in this scenario result in an estimated NPV of **-1 866 million EUR**. When compared to the costs to excavate and relocate all the phosphogypsum to the newly constructed landfills, potential benefits arising from the created marshland and reduced monitoring costs are small.

Alternative C

This alternative resulted in a NPV of **-547 million EUR**. In this alternative significant income was expected from selling phosphogypsum for construction purposes (630 million EUR), however, the investment costs remain dominant in this scenario and cannot be outweighed by the benefits, given our assumptions.

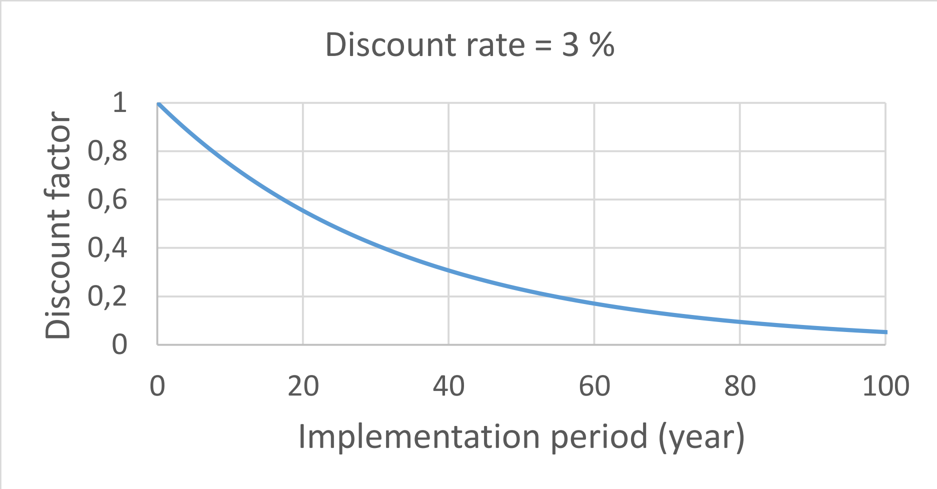

Figure 4: Discount factor with a discount rate of 3%.

3.6 Uncertainty analysis

In the uncertainty analysis, we vary the most important benefit and cost elements, as well as the discount rate and time horizon of the project, to see how realistic uncertainties in these parameter values would influence the calculated Net Present Values.

Discount rate

The current assumption is that the discount rate is 3 % p.a. This is the recommendations from the European Commission for CBAs of projects and policies/directives at the European level. However, at the national level different European countries applies different discount rates, and some (e.g. Norway) also have declining discount rates over time to better account for long-term effects. We therefore conduct sensitivity analysis with both lower (1% p.a) and higher (5% p.a) discount rates to test how this changes NPV.

Alternative A: With a 1% p.a. discount rate the NPV over 40 years would be 214 million EUR, while with a 5% p.a. discount rate NPV equals 61 million EUR.

Alternative B: With a 1% p.a. discount rate the NPV over 40 years would be -2 398 million EUR, while with 5% p.a. discount rate this value would equal -1 501 million EUR.

Alternative C: for a 1% p.a. discount rate the NPV over 40 years would be -556 million EUR, while for 5% p.a. discount rate this value would equal -522 million EUR.

Scenario time horizon

In the current analysis it was assumed that the costs and benefits would be accruing over a 40-year time period. This is a reasonable assumption when we are dealing with environmental projects, in which the benefits do not appear quickly and will last for a considerable period of time. Since in one of the project alternatives the site remediation would last for 30 years, the selected time horizon might not provide adequate estimation of the benefits. To test for this, we compare NPV for 40, 50 and 75 year time horizons, keeping the discount rate constant at 3 % p.a. The results are shown in Table 6.

Table 6: NPVs for three different time horizons

Project time horizon [years]	**Alternative A** NPV [million EUR]	**Alternative B** NPV [million EUR]	**Alternative C** NPV [million EUR]
40	117	-1 866	-547
50	149	-1 846	-521
75	197	-1 815	-481

As a result, we can see that changing the time horizon changes the NPVs for all alternatives, but still the NPV is positive only for Alternative A. For the other alternatives the remediation costs are so dominant that even long time horizons would not shift the NPV to positive values. This is also linked to the fact that costs occur early on (and is discounted little) and benefit occur later when the discount factor is becoming increasingly higher.

Exposure to workers

The assumptions made regarding worker doses have known uncertainties. It is not stated in the available documents how many working hours are spent in contact with the phosphogypsum per worker or exactly how many workers will be involved. The excavation of the phosphogypsum could cause dusting and increase the inhalation dose, if the right protective equipment is not provided. The doses could easily be 2-3 times higher than we assumed here. In this particular case, however, the increased costs of higher exposure would still be negligible compared to the total project costs and calculations were not performed.

Material partitioning and remediation time in Alternative C

In Alternative C it was assumed that 50% of the material (the most hazardous fraction) is excavated and transported to new landfills that must be constructed, 20% remains buried on-site, and 30% is sold for use in other industries. The total remediation time is assumed to be 15 years, and then the urban park and marshland benefits occur from year 15.

In an optimistic scenarios, 30 % of the material is excavated and transported to three new landfills. 60 % is conditioned for re-use and sold, and 10 % is buried on-site. The urban park will be ready after 10 years, and the marshland after 15 years. In this case, the NPV will actually change to positive taking the value of 242 million EUR. The key parameter here is the amount of phosphogypsum (PG) that can be sold. In this optimistic scenario the amount of material sold would double, and thus the benefit from selling the PG would double too. Since the amount present on the site is so large (approximately 100 million tons that can be excavated), a 50 % change in the amount to sell has a large impact on the NPV.

3.7 Distributional effects

The largest negative impacts, in the form of monetized costs, are incurred by the industry (if we assume they will pay for the remediation work). Also, their workers will get increased radiation doses while performing the remediation work.

The largest monetized benefit is experienced by the citizens of Huelva who receive recreational, aesthetic, non-use values and other benefits from the area after remediation as an urban park and/or a natural marshland. The value is higher for this group than inhabitants further away in the municipality, or in the Andalusia region.

Of the non-monetized impacts, less emissions of chemicals and radioactive substances to the environment and reduced worriedness has the greatest benefit for local residents. When it comes to increased noise and air pollution due to remediation work, transportation and construction of new landfills; these will be negative impacts for people in the larger Andalusia region since landfills will be built away from Huelva City, but within 100 km driving distance.

3.8 Recommendation

The results of this Cost-Benefit Analysis (CBA) is summarized in Table 7. Project Alternative A has a large positive NPV even when changing the discount rate and time horizon. Project Alternative B has a very large negative NPV with the same changing factors. The NPV of Project Alternative C changes from negative to positive NPV when the amount of material to be sold is increased. This indicates that further monitoring and sampling should be made to establish what the reasonable amount of PG that can be conditioned and sold could be. Alternative C could possibly take advantage over Alternative A if the amount suitable for conditioning and sale is large enough.

If no additional studies could be undertaken, so that the recommendation would be based only on the current knowledge and assumptions, Alternative A would be recommended as the best option. It has the highest NPV, lowest cost and lowest assessed uncertainty. Alternative C has a higher uncertainty and might risk ending with a negative NPV depending on the amount of phosphogypsum (PG) that is suitable for conditioning and sale. Alternative B cannot be recommended due to a high negative NPV, and very large costs that will not be outweighed by the benefits in any case.

Table 7: Overall assessment and ranking of the three different mitigating options

CBA elements	Alternative A	Alternative B	Alternative C
Monetized impacts			
Benefits	179 mill EUR	27 mill EUR	590 mill EUR
Costs	62 mill EUR	1 893 mill EUR	1 136 mill EUR
I. Calculated net present value (NPV)	117 mill EUR	-1 866 mill EUR	-547 mill EUR
Non-monetized impacts			
Benefits			
Reduced environmental impact	0	+/++	0/+
Reduced worriedness (health and safety)	0	+/++	0/+
Costs			
Increased noise and air pollution	0	-/--	0/-
II. Overall assessment of non-monetized impacts (ranking)	3	1	2
Ranking based on net social benefit (from I and II)			
Uncertainty	Interval:	Interval:	Interval:
Monetized impacts (pessimistic-optimistic)	61 to 197	-2 398 to -1 501	-556 to 242
Non-monetized impacts (qualitative assessment)	small	medium	medium
III. Overall assessment of uncertainty	small	medium	large
Ranking based om overall assessment of I, II and III	1	3	2

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Appendix A: Examples of calculation of NPV for the three Project alternative

Project alternative A								
Implemen-tation year	Year	Benefits	Benefit value EUR	Costs	Cost value EUR	Net benefit	Discount factor	Net benefit discounted
0	2019	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	1,0000	-7001814
1	2020	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,9709	-6797878
2	2021	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,9426	-6599882
3	2022	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,9151	-6407652
4	2023	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,8885	-6221021
5	2024	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,8626	-6039827
6	2025	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,8375	-5863909
7	2026	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,8131	-5693116
8	2027	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,7894	-5527297
9	2028	None	0	Implementation, worker doses	7,00E+06	-7,00E+06	0,7664	-5366308
10	2029	Urban park	1,19E+07	None	0	1,19E+07	0,7441	8845342
11	2030	Urban park	1,19E+07	None	0	1,19E+07	0,7224	8587711
12	2031	Urban park	1,19E+07	None	0	1,19E+07	0,7014	8337583
13	2032	Urban park	1,19E+07	None	0	1,19E+07	0,6810	8094741
14	2033	Urban park	1,19E+07	None	0	1,19E+07	0,6611	7858972
15	2034	Urban park	1,19E+07	None	0	1,19E+07	0,6419	7630070
16	2035	Urban park	1,19E+07	None	0	1,19E+07	0,6232	7407835
17	2036	Urban park	1,19E+07	None	0	1,19E+07	0,6050	7192072
18	2037	Urban park	1,19E+07	None	0	1,19E+07	0,5874	6982595
19	2038	Urban park	1,19E+07	None	0	1,19E+07	0,5703	6779218
20	2039	Urban park	1,19E+07	None	0	1,19E+07	0,5537	6581765
21	2040	Urban park	1,19E+07	None	0	1,19E+07	0,5375	6390063
22	2041	Urban park	1,19E+07	None	0	1,19E+07	0,5219	6203945
23	2042	Urban park	1,19E+07	None	0	1,19E+07	0,5067	6023247
24	2043	Urban park	1,19E+07	None	0	1,19E+07	0,4919	5847813
25	2044	Urban park	1,19E+07	None	0	1,19E+07	0,4776	5677488
26	2045	Urban park	1,19E+07	None	0	1,19E+07	0,4637	5512125
27	2046	Urban park	1,19E+07	None	0	1,19E+07	0,4502	5351577
28	2047	Urban park	1,19E+07	None	0	1,19E+07	0,4371	5195706
29	2048	Urban park	1,19E+07	None	0	1,19E+07	0,4243	5044375
30	2049	Urban park	1,19E+07	None	0	1,19E+07	0,4120	4897451
31	2050	Urban park	1,19E+07	None	0	1,19E+07	0,4000	4754807
32	2051	Urban park	1,19E+07	None	0	1,19E+07	0,3883	4616318
33	2052	Urban park	1,19E+07	None	0	1,19E+07	0,3770	4481862
34	2053	Urban park	1,19E+07	None	0	1,19E+07	0,3660	4351322
35	2054	Urban park	1,19E+07	None	0	1,19E+07	0,3554	4224585
36	2055	Urban park	1,19E+07	None	0	1,19E+07	0,3450	4101538
37	2056	Urban park	1,19E+07	None	0	1,19E+07	0,3350	3982076
38	2057	Urban park	1,19E+07	None	0	1,19E+07	0,3252	3866093
39	2058	Urban park	1,19E+07	None	0	1,19E+07	0,3158	3753489
							TOTAL	**117055081**

Project alternative B								
Implementation year	Year	Benefits	Benefit value EUR	Costs	Cost value EUR	Net benefit	Discount factor	Net benefit discounted
0	2019	None	0	Excavation, construction of landfills, worker doses	1,08E+08	-1,08E+08	1,0000	-1,08E+08
1	2020	None	0	Excavation, construction of landfills, worker doses	1,08E+08	-1,08E+08	0,9709	-1,05E+08
2	2021	None	0	Excavation, construction of landfills, worker doses	1,08E+08	-1,08E+08	0,9426	-1,02E+08
3	2022	None	0	Excavation, construction of landfills, worker doses	1,08E+08	-1,08E+08	0,9151	-9,91E+07
4	2023	None	0	Excavation, construction of landfills, worker doses	1,08E+08	-1,08E+08	0,8885	-9,62E+07
5	2024	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,8626	-7,33E+07
6	2025	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,8375	-7,11E+07
7	2026	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,8131	-6,91E+07
8	2027	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,7894	-6,71E+07
9	2028	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,7664	-6,51E+07
10	2029	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,7441	-6,32E+07
11	2030	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,7224	-6,14E+07
12	2031	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,7014	-5,96E+07
13	2032	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,6810	-5,78E+07
14	2033	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,6611	-5,62E+07
15	2034	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,6419	-5,45E+07
16	2035	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,6232	-5,29E+07
17	2036	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,6050	-5,14E+07
18	2037	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5874	-4,99E+07
19	2038	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5703	-4,84E+07
20	2039	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5537	-4,70E+07
21	2040	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5375	-4,57E+07
22	2041	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5219	-4,43E+07
23	2042	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,5067	-4,30E+07
24	2043	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4919	-4,18E+07
25	2044	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4776	-4,06E+07
26	2045	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4637	-3,94E+07
27	2046	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4502	-3,82E+07
28	2047	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4371	-3,71E+07
29	2048	None	0	Excavation, transportation, operation of landfills, worker doses	8,49E+07	-8,49E+07	0,4243	-3,60E+07
30	2049	Marshland, reduced monitoring	7,54E+06	Closure and revegetation of landfills	1,66E+08	-1,58E+08	0,4120	-6,51E+07
31	2050	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,4000	3,02E+06
32	2051	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3883	2,93E+06
33	2052	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3770	2,84E+06
34	2053	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3660	2,76E+06
35	2054	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3554	2,68E+06
36	2055	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3450	2,60E+06
37	2056	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3350	2,53E+06
38	2057	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3252	2,45E+06
39	2058	Marshland, reduced monitoring	7,54E+06	None	0	7,54E+06	0,3158	2,38E+06
							TOTAL	**-1,86584E+09**

Project alternative C								
Implementation year	Year	Benefits	Benefit value EUR	Costs	Cost value EUR	Net benefit	Discount factor	Net benefit discounted
0	2019	None	0,00E+00	Excavation, construction of landfills, worker doses	7,39E+07	-7,39E+07	1,0000	-7,39E+07
1	2020	None	0,00E+00	Excavation, construction of landfills, worker doses	7,39E+07	-7,39E+07	0,9709	-7,18E+07
2	2021	None	0,00E+00	Excavation, construction of landfills, worker doses	7,39E+07	-7,39E+07	0,9426	-6,97E+07
3	2022	None	0,00E+00	Excavation, construction of landfills, worker doses	7,39E+07	-7,39E+07	0,9151	-6,76E+07
4	2023	None	0,00E+00	Excavation, construction of landfills, worker doses	7,39E+07	-7,39E+07	0,8885	-6,57E+07
5	2024	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,8626	-2,92E+07
6	2025	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,8375	-2,84E+07
7	2026	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,8131	-2,75E+07
8	2027	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,7894	-2,67E+07
9	2028	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,7664	-2,60E+07
10	2029	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,7441	-2,52E+07
11	2030	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,7224	-2,45E+07
12	2031	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,7014	-2,38E+07
13	2032	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,6810	-2,31E+07
14	2033	Selling PG	6,30E+07	Excavation, transportation, operation of landfills, establishing park, worker doses	9,69E+07	-3,39E+07	0,6611	-2,24E+07
15	2034	Marshland, urban park, reduced monitoring	9,74E+06	Closure and revegetation of landfills	8,32E+07	-7,34E+07	0,6419	-4,71E+07
16	2035	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,6232	6,07E+06
17	2036	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,6050	5,89E+06
18	2037	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5874	5,72E+06
19	2038	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5703	5,56E+06
20	2039	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5537	5,39E+06
21	2040	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5375	5,24E+06
22	2041	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5219	5,08E+06
23	2042	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,5067	4,94E+06
24	2043	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4919	4,79E+06
25	2044	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4776	4,65E+06
26	2045	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4637	4,52E+06
27	2046	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4502	4,39E+06
28	2047	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4371	4,26E+06
29	2048	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4243	4,13E+06
30	2049	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4120	4,01E+06
31	2050	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,4000	3,90E+06
32	2051	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3883	3,78E+06
33	2052	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3770	3,67E+06
34	2053	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3660	3,57E+06
35	2054	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3554	3,46E+06
36	2055	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3450	3,36E+06
37	2056	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3350	3,26E+06
38	2057	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3252	3,17E+06
39	2058	Marshland, urban park, reduced monitoring	9,74E+06	None	0	9,74E+06	0,3158	3,08E+06
							TOTAL	**-5,47E+08**

Part 2 - Multi-criteria decision analysis

1. Application of multi-criteria decision analysis to environmental remediation

1.1 Introduction

As defined by the International Atomic Energy Agency (IAEA)[3], "*environmental remediation refers to reducing radiation exposure, for example, from contaminated soil, groundwater or surface water. The purpose is more than just eliminating radiation sources; it is about protecting people and the environment against potential harmful effects from exposure to ionizing radiation*". The decision process concerning remediation strategies faces multiple challenges: the complexity of dealing with (radiological) risk; various sources of uncertainty (Guillevic et al, 2018); multiple stakeholders, values, interests, perceptions, concerns; and the potential limitations in the resources that need to be allocated, amongst others.

Decision aiding tools may support the planning process for environmental remediation, by structuring the decision process, supporting the decision makers and stakeholders describe possible options, accounting for stakeholders' values in the decision process and ensuring the transparency and traceability of decision-making.

The following sections illustrate the use of MCDA for environmental decision making. A very detailed description is beyond the scope of this paper. We resume instead to exemplifying key elements in the context of environmental remediation, bearing in mind that the use of MCDA has to be to a large extent site-specific. Furthermore, not all specific interests can be represented in a generic methodology (Beinat et al, 1997).

1.2 Considerations regarding environmental remediation

Multi-criteria decision analysis (MCDA) has found increasing application as decision-aid tool (Munda, 2004). Similar to some other decision-support methodologies, for instance CBA (cost-benefit analysis) or CEA (cost-effectiveness analysis), MCDA provides a structured approach to decision making, from problem definition, over identifying decision alternatives and evaluation criteria, through to evaluating and comparing decision options. Additionally, MCDA accepts multiple dimensions (radiological, environmental, social) without forcing them into a common monetary scale (see arguments in Gamper and Turcanu, 2015), allowing for both qualitative and quantitative evaluations of the impact pf remediation strategies. In MCDA one seeks to build multiple criteria representing several points of view, instead of using a single criterion (e.g. economic in case of CBA) accounting for all the dimensions of the decision problem studied (Roy, 1996). Roy and Vincke (1981) pointed out already in the 80's that the role of MCDA is not to replace the decision-maker with a mathematical tool, but to support his/her decision by a clearer illustration of the multiple factors affecting the performance of potential decision options.

[3] https://www.iaea.org/OurWork/ST/NE/NEFW/_nefw-documents/Environmental_Remediation.pdf

MCDA is deemed particularly suitable for environmental decision-making problems (Gamper and Turcanu, 2015), which are characterised by complex policy contexts, with multiple, potentially competing objectives and value systems, that cannot be easily quantified. It can serve for the systematic comparison and ranking of policy options or laying out the basis for future policies.

Currently there are few legal requirements prescribing MCDA for environmental remediation. However, references can be found in UN and EU policy recommendations (UNFCC 2002, EU Guide to Socio Economic Development 2003), and more specifically linked to environmental remediation in guidance from IAEA (2002), ICRP (1989) and a number of European research projects (CARE, EVATECH, RESTRAT).

Furthermore, it is argued that MCDA is particularly well suited for integration within participatory processes for decision-making on environmental issues, since it can structure the structure the decision process, increase transparency about the plurality of factors and values included in decision-making and support the search for a good compromise solution. As argued by IAEA (2002), the main challenge for applying MCDA to environmental remediation is that the methodology should live up to its "claims of making more explicit the ways that alternatives are evaluated and compared" and "embed technical aspects into deliberative decision-support processes" (pp. 25).

At the same time, in order to meet the expectations that decision processes for environmental remediation provide opportunities for stakeholder involvement throughout the process, MCDA should integrate stakeholder participation in decisions on the set of alternative options; the set of evaluation criteria; the evaluation of impacts for the potential decision options; the weights or other inter-criteria information; the method to be used to compare options; and, most importantly, the role to be given to the MDCA in the (participatory) decision process at hand. Van den Hove (2006) points out the importance to clarify the way decisions will be taken on the aforementioned elements, documenting dissenting opinions and defining in a transparent and participatory way the "*procedural role of MCDA in the decision process*" (pp. 15).

As mentioned in the IAEA recommendations, (https://www.iaea.org/OurWork/ST/NE/NEFW/_nefw-documents/Environmental_Remediation.pdf), "*an important factor for a successful remediation project is for those people whose lives are affected by the contaminated site to be involved in and to contribute to the remediation process as they have a stake in the end result. It is not only an ethical matter but a moral obligation to involve various stakeholders in the remediation process. Listening to stakeholders' opinions, capturing their perspectives and taking them into account from the very beginning of the remediation process assists the decision making process for taking the most appropriate approach*".

1.3 Steps in multi-criteria decision analysis

Multi-criteria decision analysis may be structured in several steps (see e.g. Keeney 1992; Roy, 1996; Dodgson et al, 2000; Munda, 2004), as illustrated in Fig. 1. In the following sections we look in detail to some elements of the MCDA process.

1.3.1 Formulation of the decision problem

Although commonly encountered in practical applications for ranking different decision alternatives, multi-criteria decision analysis may support decision-making on environmental remediation strategies in various ways, for instance:

- methodological description of the possible environmental remediation options in a structured and systematic manner - description problem (Roy, 1996);
- identifying or constructing the environmental remediation strategy that best meets certain aspiration or goals (e.g. residual doses below a specified value, or achievement of a desired end state) – design problem (Belton and Stewart, 2002);
- determination of the best remediation option or the set of best possible options - choice problem (Roy, 1996);
- determination of the best subset of remediation options, given the possible interactions and synergies between them (e.g. a combination of agricultural countermeasures for post-accident management) - portfolio problem (Belton and Stewart, 2002);
- ranking environmental remediation options based on their overall performance - ranking problem (Roy, 1996).

While ranking has often been postulated as the final aim of an MCDA for environmental remediation (Hedemann-Jensen, 1999), the analysis could also serve to describe the problem in a structured way ("description problem") in order to identify the advantages and disadvantages of the different remediation options.

Example: The main objective of the assessment process could be to identify a sustainable remediation strategy for a contaminated site. One of the ways to define this is the elimination and/or control of unacceptable risks in a safe and timely manner, whilst optimising the environmental, social and economic value of the work.

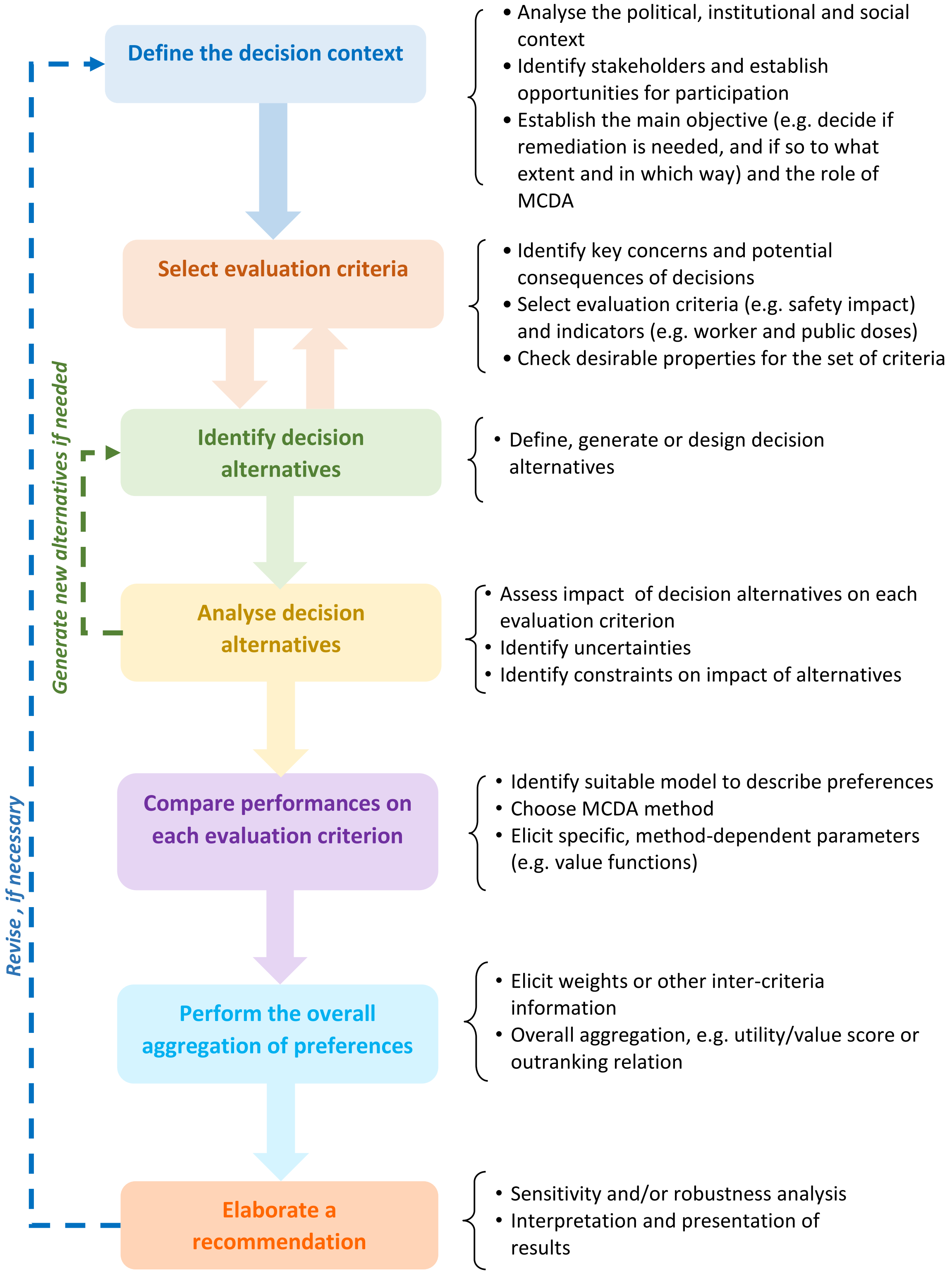


Fig. 1 Basic steps of a multi-criteria decision analysis process

1.3.2 Decision alternatives

The set of potential decision alternatives should include all environmental remediation options that are "*temporarily considered as realistic by at least one of the actors, or assumed as such by the analyst*" (Roy and Bouyssou, 1993). The definition of decision alternatives depends both on the problem itself and the actors involved, and influences the subsequent methodological steps.

Currently there exists a range of remediation technologies, described in guidance documents such as the European Handbooks on the management of inhabited areas and contaminated food production systems (see https://eu-neris.net/library/handbooks.html) or the Wiki compendium of technologies of the IAEA IDN network (https://nucleus.iaea.org/sites/connect/IDNpublic/Pages/IDN-Wiki-Introduction.aspx).

Feasibility and applicability of remediation technologies are important factors (Nisbet et al, 2005; Raskob et al, 2010). In some cases, "*the available technologies are not adequate to achieve the desired goals and further development is needed*" [1]. Additionally, regulators may favour proven technologies[4]. This shows that the set of potential decision alternatives may evolve during the process in order to accommodate the site-specific constraints on the remediation options.

Example: Decontamination techniques applied in the special decontamination area around Fukushima NPPs made use of the European handbooks, but 28 additional options have been developed, with focus on conventional techniques utilizing existing, rather than specific equipment. Two reports in English are available containing technical details such as decontamination factors and external doses to workers: http://jolissrch-inter.tokai-sc.jaea.go.jp/pdfdata/JAEA-Review-2014-051.pdf ; http://josen.env.go.jp/en/policy_document/pdf/decontamination_report1503_full.pdf.

The evaluation of impacts may also lead to reconsideration of the initial alternatives (therefore the green coloured feedback loop in Figure 1). For instance, if transport of waste dump material is perceived as dangerous by local residents, a remediation option involving the displacement of the material may initially be assessed as having low social acceptability. However, if improvements are proposed for transportation of material in consultation with local actors, e.g. by securing the trucks with covers preventing the spread of dust during transport, the acceptability of the amended remediation option might increase. Another example of reconsideration of initial options (e.g. due to excessive costs) may be decreasing the geographical area where a particular remediation technology will be applied.

If any pre-screening of remediation options is carried out (e.g. based on feasibility considerations), the justification of the screening and the decisions underlying the selected options should be well-documented and discussed with all stakeholders.

1.3.3 Evaluation criteria

The dimensions to be considered in assessing the different remediation alternatives are included in a MCDA model through a set of criteria against which the impact of the decision alternatives will be evaluated.

There are various ways to build a set of evaluation criteria, essentially differentiated as:

[4] Getting to the Core of Environmental Remediation Reducing radiation exposure from contaminated areas to protect people. IAEA. https://www.iaea.org/sites/default/files/18/05/environmental_remediation.pdf

- top-down: starting from a main, overall objective (e.g. a desired end state, a sustainable remediation strategy, or BATNEEC - best available technique not entailing excessive costs), a hierarchical tree structure is built of key concerns or sub-objectives (Keeney, 1992; Bana e Costa and Beinat, 2005), with the end nodes being quantitative or qualitative indicators;
- bottom-up: starting from effects or consequences of potential decisions, a consistent family of evaluation criteria is built (Roy, 1996) by partial synthesis of related items, provided these do not correspond to conflicting points of view (e.g. costs for food producers and for the polluter should not be added to a single economic cost).

In practice, a combination of the two approaches may prove efficient (Bana e Costa and Beinat, 2005).

Example of effects or consequences of remediation options: Environmental impact assessment assesses the possible changes in the various environmental criteria. Based on the reversibility, spatial extent, duration and intensity of these changes and the sensitivity of the considered environmental criterion, the significance of the impact is then evaluated. For simplicity, the environment can be divided in three sub-environments: physical, biological and socio-economic environment. Several factors should be considered, the impact of which has to be evaluated for the different phases of remediation (e.g. before remediation, during remediation works, short term after remediation, long term after remediation).
This distinction of the environment into the different sub-environments is artificial, and there may be overlaps between the different sub-environment. Not that the list below might serve as a starting point in defining a list of evaluation criteria, rather than the final list of criteria.

Physical environment

Air quality refers to the levels of pollutants (also dust) in air. To protect the public health, regulatory limits are available for dust and various pollutants (e.g. SO_2, NO_2, CO, radon) in air that can be discharged by industry, transport, and other activities. Also radon in- and outdoors can be an issue. Regulatory limits are available for radon indoors, while the outdoors levels can be compared with background levels.

Noise or vibration refer to the environmental degree of noise or vibration pollution (during remediation works). These can have a negative impact on human's health and quality of life. There exist environmental quality standards for both noise (in dBA) and vibration (in dB). The environmental conditions (residents nearby, breeding place for red list biota, etc.) will considered in the quality evaluation.

Water quality refers to of the physico-chemical and radiological characteristics of water. The levels of radionuclides and non- radioactive pollutants in surface and groundwater are compared with national, and if not available international, standards. Water use of these sources will be taken into consideration when evaluating the levels.

Soil quality (structure, pollutants) refers to the capacity of the soil to maintain its normal function within the considered ecosystem. Non-radiological and radiological levels are compared with soil quality standards as well as changes in the structure of the soil that may have an impact on future land use.

Biological environment

Fauna and flora refer to the biodiversity of the considered ecosystem with focus on endangered (red list) species.

Public/workers health and safety

Workers and public can be exposed to hazardous substances through various pathways: external (radiation, skin) or internal exposure (via inhalation, ingestion)). So while the physical criteria may not be exceeded, the human impact, depending on the exposure scenario, may be important. The health risks to humans (workers, public) from exposures at remedial sites need to be assessed by considering the site-specific exposure pathways. The impacts from radiological as well as non-radiological pollutants need to be evaluated and compared with standards. In addition, the possible unplanned event (e.g. landslide) caused by the remedial activities, may also need to be considered. which is considered in the 'safety' criterion.

Socio-economic environment

This environment related to the changes in the social and economic environment. Depending on the site, there are different aspects to be considered, including, for instance:

- Wellbeing/disturbance of community
- Cultural heritage
- Employment
- Ecosystem services relates to the provisioning services of the environment such as food and water; regulating services such as climate and water balance, natural erosion protection; supporting services such as soil formation, crop pollination and nutrient cycles; and cultural services such as recreational and other non-material benefits.
- Infrastructure. Extra infrastructure can increase the living standards.

Example of indicators covering the social dimension of sustainable environmental remediation Harclerode et al. (2015) identified 10 indicator categories covering the social dimensions of sustainable remediation decision-making: health and safety, economic stimulation, stakeholder collaboration, benefits for community at large, alleviation of undesirable community impacts, equality issues, value of ecosystem services and natural resources, risk-based land management and remedial solutions, regional and global societal impacts, and contributions to other policies.

Bouyssou *et al* (2000) draw attention, however, that defining a list of criteria where each possible aspect of the complex object of evaluation is considered, for instance based on literature, experience or international regulations and guidelines, might provide "*an abstract collection of attributes, independent from the specific problem at hand, thus containing redundancies and conceptual dependencies which can invalidate the evaluation*" (pp. 20).

Munda (2019) recommends that a good balance should be kept between representing the reality as well as possible, potentially leading to a large number of criteria and lack of transparency of the process, and maintaining the simplicity and clarity of the model without over-simplification of reality.

Roy (1996) advises that the **set of evaluation criteria** should be:

- **exhaustive**, i.e. all factors that can influence the preference of any actor for one or another remediation option have been considered;
- **cohesive**, i.e. preferences expressed with respect to each individual criterion are consistent with the global preferences;
- **non-redundant**, i.e. the elimination of any criterion leads to violation of exhaustiveness or cohesiveness.

Keeney (1992) argues that evaluation criteria should be **essential**, i.e. addressing fundamental aspects; **controllable**, i.e. influenced only by the chosen decision alternatives; and **operational**, i.e. allowing impact assessment within reason of available time and resources.

Example of evaluation criteria: Beinat et al (1997) drafted an MCDA methodology for soil remediation. Their decision-support approach (REC) considers:

- Risk reduction: the degree to which the remediation reduces the risk for humans leaving on site (people who work or leave on or near the contaminated site), biota or other targets on site (e.g. monuments).
- Environmental merit: including all environmental impacts, both benefits (e.g. clean groundwater as a result from remediation) and negative aspects (e.g. air or surface water pollution, final waste) resulting from the contamination or the remediation process that are not included in Risk
- Costs.

Care is taken to avoid overlaps between criteria, for instance by including in the category "Environmental merit" only those aspects of general interest, whereas the risk category focuses mainly on the local impact.

Each of the three aforementioned dimensions includes several other factors which are quantified. For instance, the improvement in soil quality is quantified taking into account the target values (derived from environmental policy objectives) and intervention values (derived based on human- and eco-toxicological effects).

The REC methodology exemplified above does not include social criteria; however, the methodology can be used to evaluate the different options from a technical and economic point of view.

An evaluation criterion generally induces an ordering of alternatives. However, even if the criterion cannot be linked to a natural attribute, it is often possible to find an ordinal scale allowing to evaluate the performance of potential decisions (Belton and Stewart, 2002). For instance, the impact with respect to the criterion "Feasibility" might be assessed on the scale "not feasible", "feasible with constraints", "feasible". Belton and Stewart (2002) provide an example of qualitative scale for water quality, containing the categories "very bad", "poor", "status quo", "good", "excellent".

In general, a qualitative scale should be valid and reliable, allowing unambiguous scoring of new alternatives and identical scoring by independent assessors (Belton and Stewart, 2002). The scale should also be "relevant to the objectives of the decision process" (idem).

In some MCDA applications, qualitative criteria such as social acceptance, are further explicated by means of quantitative indicators, e.g. the amount of surface or subsurface area required to manage the contaminated sediment in a study by Kiker et al (2005). The authors mention that such indicators may draw on research, monitoring, and survey studies, or be the result of expert judgment elicitation.

In the presence of uncertainty, the evaluation of the impact of a remediation option with respect to a specific criterion cannot be captured in a unique element. In such a case, the impact on an option may be modelled with an interval of values, a probability distribution, or a fuzzy set, amongst others.

1.3.4 Preference modelling and MCDA method

Depending on the way global preferences are modelled, several types of MCDA methods have been proposed, for instance: multi-attribute value/utility (MAVT/MAUT) methods, seeking to aggregate all points of view into a unique function which is to be optimised; outranking methods, which construct and exploit a synthesizing relation based on the decision maker’s preferences; and distance based methods which seek to identify those alternatives that best satisfy desired performance levels.

While the former two could be better suited for a risk-based approach to environmental remediation, the latter could support the development of strategies to reach a specific end-state approach, by constructing a solution that satisfies the aspiration levels of the decision-maker. A key element in choosing the MCDA method is the degree of compensation that can be allowed between the various criteria: MAVT/MAUT and distance-based methods are compensatory (in the sense that weak performances on some criteria may be compensated by good performances on other criteria), whereas outranking methods are in general non-compensatory.

Table 1 illustrates with literature references the variety of MCDA methods that have been proposed or tested for environmental remediation scenarios and projects.

Table 1 Examples of MCDA literature studies related to environmental remediation

Reference	MCDA Method	Remediation / environmental decision-making criteria
Al-Rashdan et al (1999) Ranking environmental projects in Jordan	PROMETHEE and Judgmental Analysis System software	Derived with experts through Nominal Group Technique and Value focused thinking. Objective tree consisted of - Main goal: balanced social and economic development - Higher objective: sustainable development of water resources - 15 Fundamental objectives: water supply, urgency, irreversibility, effects human health, low of amenity, number of people affected, effects on water quality, certainty of outcome, technical feasibility, economic feasibility, cultural feasibility (acceptability), effectiveness, institutional and legislative feasibility, flexibility, opportunity.
Yang et al (2012) Remediation of petroleum contaminated sites	Fuzzy TOPSIS combined with integrated process modeling (using BIOPLUME III)	Academic study. Criteria: • Risk at the contamination source center • Risk at the residential area • Risk at the supply well • Risk at the primary school • Installation cost • Operation and maintenance cost
Linkov et al (2006a)	Review of MCDA application for environmental management, in particular contaminated sediment management. Case study of contaminated sediment management in New York / New Jersey Harbour. Multi-attribute value method with SMART weighting of criteria. Software used: Criterium Decision Plus.	Proposes a basic decision analytic framework that couples MCDA with adaptive management and its public participation and stakeholder value elicitation methods. Criteria: • Cost • Human health (Maximum cancer probability (non-barge worker; number of complete human health exposure pathways; estimated fish COC concentration in fish / hazard level) • Ecological health (Ecological hazard quotient) • Public acceptance: Ratio of impacted area to facility capacity Different weighting by two stakeholders (EPA and USACE).

Arvay and Gregory (2003) mentioned in Linkov et al (2006a) Case study on cleanup priorities at contaminated sites	Multi-attribute utility theory (MAUT) with SWING weighting	Compares a “science-based” approach with a “value-based” approach. In the science-based condition, subjects were presented only with technical information relating to the level of contamination and the human and environmental health risks at each of the three sites. In the value-based condition, information related to the severity of contamination at each of the three sites was linked explicitly to societal values and to personal objectives for the cleanup activities.
Petelina et al, (2014) mentioned in Harclerode et al (2015) **Gunnar Mine** Project, Northern Saskatchewan, Canada (abandoned U mine site: unconfined U tailings , gamma radiation in excess of acceptable levels)	Analytical Hierarchical Process used to capture stakeholders’ opinion. Software used: ExpertChoice Life Cycle Assessment used for (expert) quantitative assessment. Stakeholders: selected from employees, but representing 5 interest groups.	Academic study for 4 remediation options 9 sustainability criteria selected from an initial list of 20 environmental, social and economic criteria: • Biodiversity (env.) • Air quality (env.) • Greenhouse gases (env.) • Occupational risks (socio.) • Community involvement (socio.) • Land use (socio.) • Project cost (eco.) • Project risks (eco.) • Economic opportunities (eco.)
Linkov et al (2006b)	Review of MCDA applications for various environmental problems including management of contaminated sediments and aquatic ecosystems. Case study Cocheco river: PROMETHEE, DecisonLab 2000 software.	Alternatives defined by experts. Criteria defined through semi-structured interviews with representatives from different stakeholder groups: cost, environmental quality (qualitative), ecological habitat (acres), human habitat (acres).
Shershakov et al (2009)	Multi-attribute value theory (MAVT) generic guidance. Case studies of remedial actions in freshwater ecosystems (MAVT, additive value function); forest ecosystems (interval valued evaluations of effectiveness as dose reduction and acceptability, PRIME decision rules e.g. min-max regret); rural areas (ReSCA software; utility as weighed sum of cost per averted dose and acceptability – derived with questionnaires)	Example given for construction of a utility function in the criteria space collective dose vs. financial cost of remediation strategies. Suggests that key elements in the decision process for remediation after nuclear accident are radiological factors (dose distribution, i.e. are exposure levels acceptable from a radiological standpoint), economic factors (available resources, funds, etc, i.e. are measures supported with available resources) and socio-psychological factors (situation acceptability, i.e. will decisions bring back credibility)

Yatsalo et al (2011)	Software: DECERNS Geospatial application of Multi-attribute value theory (MAVT) The study suggests integrating spatial information (e.g., land use, population density, infrastructure such as the location of roads, railroads, and so forth) with MCDA criteria.	Academic study: management of contaminated milk, using the Fukushima accident as a case study. Criteria identified by experts: • Cost • Avertable collective dose • Fraction of the local population in each settlement with mean internal dose above 1 mSv/y • Fraction of milk produced with contamination above 100 Bq/L • Socioeconomic indicators
IAEA (2002) Case study D: optimising the remediation of sites contaminated by uranium mining	Multi-attribute analysis suggested as the suitable method	Costs: implementation of remedial action; water treatment; maintenance, monitoring; additional land required Health risks: radiation, chemical toxicity, accidents (during and after remediation; workers and general public), Acceptance: socio-economic aspects (employment); quality of life factors; institutional factors; ecological aspects, management of scarce resources
Mustajoki et al (2007) Evaluation of management options for urban clean-up after a nuclear accident.	MAVT, weights determined using the SWING method WebHIPRE software Stakeholder involvement through decision conferences.	Academic study with local stakeholders' involvement. Linear additive value function aggregation. method. Initial value tree of criteria simplified to a final value tree containing health effects (number of cancers), costs (direct), socio-psychological impact (anxiety and reassurance), environment. The integrated view focusing on protection of the whole inhabited environment is suggested to increase the satisfaction with the method (as compared to addressing one environmental segment at a time).

1.3.4.1 Multi-attribute value methods

One of the most widely applied class of MCDA methods stems from multi-attribute value theory (MAVT). This approach assumes that the preferences of the decision-maker are consistent with a value function V, which equates the preference of an alternative *a* over another alternative *b* with the relation V(*a*)>V(*b*). in the case when V(*a*)=V(*b*), the two alternatives are judged as indifferent[5].

In the case of an additive value function, the value V(*a*) of an alternative *a* may be described as a weighed sum of the marginal value functions v_i corresponding to the evaluation criteria:

$$V(a) = \sum_{i=1}^{n} w_i v_i(a)$$

In the expression above, w_i represents the weight if the *i*-th criterion. The weights are generally normalised such that their sum is equal to 1. As this type of aggregation is deemed to be most easily explained to, and understood by decision-makers (Belton and Stewart, 2002), it is also frequently encountered in practical applications.

This category of MAVT methods require that the set of evaluation criteria satisfies the property of preferential independence. This means that preference orderings in terms of any subset of criteria should not depend on the level of performance on other criteria. Belton and Stewart (2002) provide an example to illustrate this, involving the creation of a recreational area. In this example, the pair of criteria relating to the person*days of recreational time and the number of biota species conserved is not preferentially independent on the investment cost, since restrictions on the use of recreational area in order to achieve a higher conservation rate would possibly be more difficult to justify if the investment costs were very high.

The requirement for preferential independence may be relaxed by the use of multiplicative, rather than additive value aggregation models. However, in most practical problems it is preferable to use the additive model, due to its simplicity, resolving instead the preferential independence issues by a suitable choice of criteria. In the example above, it is suggested for instance to use the person*days of recreation and number of species conserved per unit investment cost as a way to deal with preferential independence.

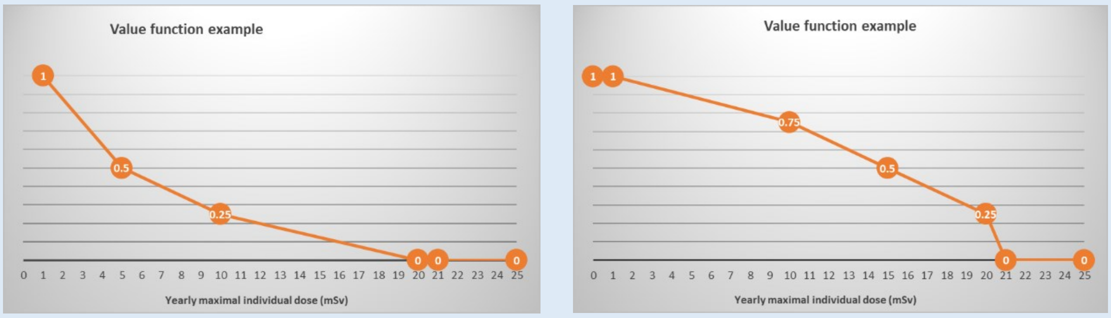
Example of method for building value functions for quantitative criteria:

When using MAVT, it is recommended that value functions v_i are standardised, e.g. taking values between 0 and 100 or 0 to 1). One possible method for building a monotonous value function is the bisection method:

1. Define the end points of the scale p_1 and p_2: these can represent the worst and best points, or alternatively, the "neutral" and "good" points. Scores outside this interval have either value 0 or 1.
2. Establish whether the function is increasing (highest value is most preferred) or decreasing (criterion to be minimised).

[5] The existence of such a function implies among others that if an alternative *a* is preferred to *b*, and *b* is preferred to *c*, then *a* must necessarily be preferred to *c*, and similarly for indifference. If such a condition does not hold, an alternative method has to be used, for instance an outranking MCDA method which allows specifying preference and indifference thresholds.

3. Identify the point on the scale corresponding to the midpoint from a value point of view (has value 0.5), i.e. the variation in value from p_1 to the midpoint has the same magnitude as from the midpoint to p_2.
4. Continue until the decision-making preferences are well captured (5 point estimates are considered rather robust), see some artificial examples in Fig. 2.



a) b)

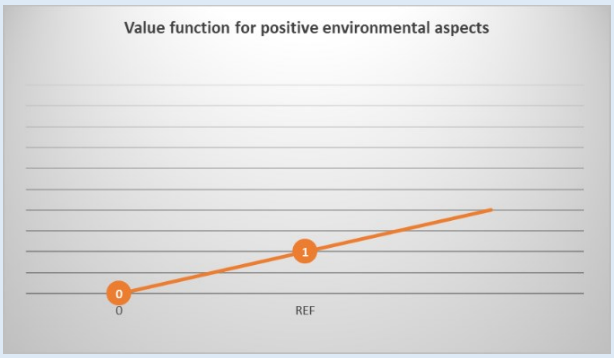
Fig. 2. Value functions (artificial examples) for maximal individual yearly dose, if one aims at a dose as low as reasonably achievable, within the 1-20 mSv per year range. The value function in example a) represents more risk aversion than the value function in example b).

Example of building value functions for environmental quality factors for soil remediation

Beinat et al (1997) first quantify the different environmental impacts aspects and subsequently transform them to standardised values by means of value functions. Quantification is based on intervention values (requiring remediation), target values (characterising unpolluted soils) and indicative values. Target values are usually one or more orders of magnitude lower than the intervention value. In case of substances that occur naturally in soil, target values depend on natural background concentrations in non-contaminated areas.

The REC methodology further proposes defining value functions for various environmental quality aspects based on status quo (no remediation) and reference performance levels for all aspects. The reference performance levels correspond to "*what is judged by soil experts as being an average soil remediation case in current practice*" (Beinat et al, 1007).

Value functions are then constructed as linear functions with negative values for negative environmental aspects (e.g. emissions into surface water, amount of final waste or prevention of groundwater contamination) and positive values for positive environmental aspects (e.g. clean soil). For negative aspects the value of the reference performance is set to -1, whereas for positive aspects the reference performance has the value 1.



Example of method for building value functions for qualitative criteria (Belton and Stewart, 2002)**:**

1. Suppose a qualitative criterion is a mix of different factors, and for each of these factors it is possible to describe what constitutes a favourable, acceptable or unfavourable impact or situation

3. The value function could be constructed for instance as follows:

- All factors are favourable: value 10
- Balance of factors is better than all acceptable: value 7.5
- All factors are acceptable or there is at most one unfavourable factor, which is balanced by a favourable factor : value 5
- Balance of factors is worse than all acceptable: value 2.5
- No factors are favourable and half or more factors are unfavourable: value 0

1.3.4.2 Outranking methods

Outranking methods rely on less strong theoretical assumptions than MAVT methods. It is for instance not required any more than any two actions are (globally) comparable, or that the indifferences are transitive, or that any subfamily of criteria is preferentially independent on the other criteria.

The underlying principle of outranking methods (Roy and Bouyssou, 1993) is the "democratic majority, without strong minority". In other words, an alternative outranks another, if it performs better on a majority of criteria ("concordance"), and there is no criterion for which the second alternative is strongly better than the first ("non-discordance").

The main steps of an outranking method generally entail pairwise comparison of actions on each criterion, building of an outranking relation aggregating these preferences and exploitation of the outranking relation in order to derive a recommendation.

Instead of a value function, preferences can be for instance expressed using the (possibly variable) indifference and preference thresholds.

If criteria weights are available, the outranking relation may be built for instance on the basis of concordance and discordance indices like in ELECTRE I-III methods (Roy and Bouyssou, 1993) or based on outranking degrees as in PROMETHEE methods (Brans et al, 1984). The meaning of weights is however different than for the MAVT/MAUT methods: for outranking methods they represent intrinsic importance coefficients.

If criteria weights are not available, other outranking methods may be used instead.

In order to avoid procedural biases which may result in undesired side effects such as rank reversal, robust aggregation methods can be used to assess comprehensive preferences (Vincke 1999). A robust outranking method has the property that its solutions, derived from different admissible method-specific parameter sets, do not contradict each other.

Example of constructing an outranking relation (Vincke, 1999)

- Consider n criteria g_1, .., g_n evaluated on quantitative scales or qualitative ordinal scales.
- Associate with each criterion g_i a weight w_i. We can assume that $w_i > 0$, $\forall i$, and that the weights are normalised such that their sum is equal to 1.

- For any subsets C and D of criteria, assume that:

  If the set C of criteria is judged more important than D, then $\sum_{i:g_i \in C} w_i > \sum_{j:g_j \in D} w_i$

  (this importance relation has to have some natural consistency properties, see Vincke 1999)
- Select a value $k \in [0.5, 1]$. Then for any two alternatives *a* and *b*, *a* outranks *b* globally, if and only if
  i. *a* is at least as good as b on all criteria; or
  ii. the set C of criteria for which *a* is preferred to *b* is more important than the set of criteria for which *b* is preferred to *a*, and $\sum_{g_i \in C} w_i \geq k$

The resulting outranking relation can be further exploited to derive a ranking of decision alternatives. Due to the specifics of the outranking relation, some alternatives may not be comparable (there are insufficient arguments for deriving either that *a* outranks *b*, or that *b* outranks *a*).

Outranking methods are in general non-compensatory, as opposed to the MAU/VT methods. This implies that a strong disadvantage in an important criterion might not be compensated by advantages on a number of less important criteria.

Examples of the use of outranking methods for environmental decision-making can be found in Linkov et al. (2006).

1.3.4.3 Weighting the evaluation criteria

In order to aggregate the partial evaluations of remediation options, some information about the importance of the different factors or sub-factors has to be specified. Most of the times, this information takes the form of numerical weights, although other methods are also possible (e.g. pairwise comparison of criteria). Weights are usually normalized such that they take values in (0, 1) and their sum is 1.

In MAVT methods, weights have the meaning of trade-offs between criteria. They can be derived either for all attributes (factors) at the same time, or separately for each level in the value tree, e.g. first assign weights for all sub-factors pertaining to "Economic", "Social", and "Technical" separately, and afterwards attribute weights to the Economic, Social and Technical dimensions. There are different methods that can be used to derive numerical weights, for instance:

- SWING
  - Consider a fictitious decision option which has the worst impact for all factors; choose the attribute for which the shift from worst to best value would be the most valuable improvement and give this attribute a score 100;
  - Choose another attribute to be improved and give points from 1 to 100 using the first attribute as reference; continue until all attributes have received scores;
  - Normalise weights such that their sum is equal to 1.
- Pairwise comparison of criteria
  - This information can be transformed to numerical weights compatible with the pairwise assessment using the AHP method of Saaty (1984), which is for instance included in the WebHIPRE MAVT software package.

Example: SWING weighting for value functions in REC (Beinat et al, 1997)

In the REC approach for soil remediation by Beinat et al (1997), environmental costs and benefits are standardized through value functions with respect to a reference performance. Value functions are therefore not constrained in a pre-defined interval.

In this approach weights are derived by asking questions relating to swing pairwise comparisons. Assuming that the reference performance for a factor "soil loss" is 460 m^3 of soil, whereas for the final waste is 300 m^3, the questions assess first the preference between the two factors, then the degree of preference: *Would you prefer to prevent the loss of 460 m^3 of soil or to prevent 300 m^3 of final waste?* If the expert preferred to prevent the loss of 460 m^3 of soil, he would then be asked: *If the quantity of final waste prevented were multiplied by x, would you still prefer to prevent the loss of 460 m^3 of soil?* This question is repeated until a suitable *x* value is established; this can be translated into the relation $w_{waste} * x = w_{soil\text{-}loss}$.

This process has to be checked for inconsistencies in answers. Beinat and colleagues suggest that by averaging out inconsistencies, the reliability of these values can be enhanced.

In outranking methods, the meaning of weights is that of intrinsic importance of criteria, thus they can be used as generic values irrespective of the performances of the different remediation options and can thus be easier prescribed in a regulatory framework. For instance, the three main categories of impacts (technical-social-environmental) might receive equal weight on the basis of ethical considerations. Care has to be taken however that assigning weights as intrinsic importance coefficients is not consistent with the use of MAVT/MAUT, where they are required to represent trade-offs, but rather with the outranking methods methodology.

Eliciting numerical weights is considered as one of the most difficult parts of MCDA. Furthermore, as illustrated for instance by Linkov et al (2006), different stakeholders may have different priorities which may result on different ranking of remediation alternatives.

Bana e Costa and Beinat (2005) identified three possible operational frameworks for the application of MCDA: i) individual problem structuring and evaluation; ii) group structuring and individual evaluation; or iii) group structuring and evaluation, where individual may refer to one stakeholder. Renn et al (2005) suggested a division of tasks at three societal levels: where development of decision alternatives and evaluation criteria is done with participation of all relevant stakeholders; impact assessment of the various options mainly by experts and the weights of criteria are established in a citizens' panel.
Important considerations to keep in mind are that:

- The importance of criteria, and therefore their weights, may be assessed differently by different stakeholders;
- Even technical experts can have diverging views on the importance of different criteria;
- The points of view of the different stakeholders should be reflected in the analysis and taken into account, for instance allowing for individual evaluation of weights by different stakeholders and highlighting the different rankings ensuing from this (see e.g. Beinat et al, 1997).

1.4. Dealing with uncertainty

There are different sources of uncertainty that may affect the MCDA result, for instance related to criteria scores, to the preference modelling for individual criteria (e.g. values function in MAVT or indifference and preference thresholds in outranking MCDA methods), or the inter-criteria importance information (e.g. weights).

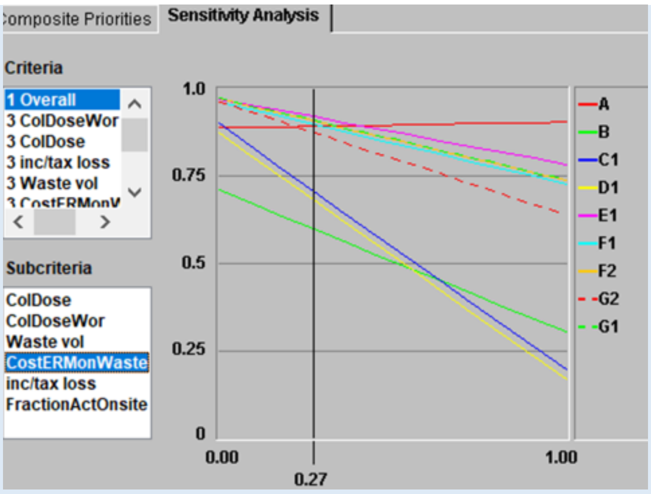
Uncertainty can be accounted for in MCDA in various ways, for instance:

1. the use of sensitivity analysis to study the extent to which the uncertainty in the MCDA model output (e.g. the final ranking of alternatives) can be apportioned to the different sources of uncertainty in the model input; or ii) to study the extent to which model parameters (e.g. weights) can be changed without altering the model results (e.g. the final ranking or the top-most ranked alternative);
2. the use of uncertainty analysis to study the effect of varying model parameters (e.g. weights, thresholds, etc.) and/or impact scores of the different remediation alternatives. This can be useful to show first how the impacts and values of different remediation alternatives can change, as well as how the overall rank of an alternative may change. In such a case, one possibility is to look for robust solutions that perform reasonably well irrespective or the variation in scores or model parameters;
3. the use of utility functions, instead of value functions, whereby alternatives are ranked depending on their expected utility. This increases however the complexity of eliciting model parameters and reduces the practical appeal of MCDA. Hämälainen et al. (2000) reveal for instance based on a case study in Finland that evaluating uncertainties was difficult for the participants and the incorporation of probabilities problematic.
4. translation of the uncertainties in the impact scores into preference and indifference thresholds in outranking methods. For instance, if scores for an alternative *a* with respect to criterion c may vary with ±20% then a (variable) indifference threshold for alternative *a* might be set as $i(a)=0.2*c(a)$. In other words, since the value of $c(a)$ can be 20% higher or lower, an alternative that has an impact within 20% range of $c(a)$ might be considered indifferent to *a*. The preference threshold can for instance be $p(a)=2*i(a)$, indicating the level from which we have strict preference.
5. robustness analysis, i.e. determining solutions that perform “reasonably well” under any possible future, or irrespective of the specific values that the model parameters or the impact scores may take within their domains.

While some question the subjectivity of the MCDA model or its results, Belton and Stewart (2002) suggest that the MCDA analysis can be a used as a “sounding board for intuition”.

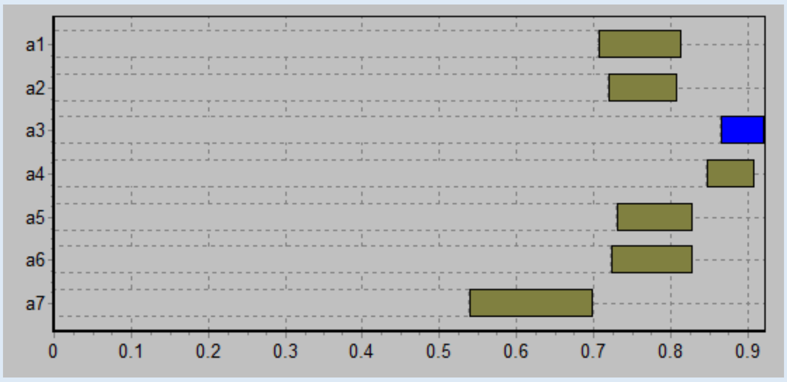
Example of sensitivity analysis on criteria weights

The WEB-Hipre MCDA software (http://hipre.aalto.fi/WebHipre.html) allows visualizing the effect of changing the weight of a criterion on the final ranking of alternatives. In the example below, the weight of cost of environmental remediation can be varied from an initial value of 0.27 (where alternative E1 comes forward as the best option) to check the effect on the final ranking (e.g. if the weight of cost increases to 0.45, alternative A may become the preferred one).



Example of using uncertain information on the importance of criteria

The VIP software of Dias and Clímaco (2000) uses uncertain information about criteria weights expressed as inequalities (e.g. $w_1+w_2 \geq w_3$, which describes the fact that criteria 1 and 2 together are at least as important as the third criterion) to represent graphically the variation in the overall performance of the decision alternatives. In the example below, alternative a_3 seems to be a robust solution, as it is clearly better than all other options except a_4 and performs reasonably well in all cases.



A similar visualization may be helpful also for a more comprehensive uncertainty analysis which considers also uncertainty in the alternatives' impact scores.

1.5. Accounting for social uncertainties

Guillevic et al (2018) identified several societal uncertainties relating to NORM contaminations. In the following we reflect on the way Multi-Criteria Decision Analysis (MCDA), as tool or as a process, can support addressing these uncertainties.

The analysis of regulations and guidance related to NORM situations (Guillevic et al, 2018, pp. 43) highlighted a list of key issues which may give raise to societal uncertainties, among which:

- how to proceed with communication and stakeholder engagement in environmental remediation programmes;

As a process, multi-criteria decision analysis may include participation in all the steps of the process, from the formulation of the problem (e.g. the need for remediation, the desired end-state), through to criteria for evaluation remediation strategies and defining preferences.

- concerns and expectations from a wide field of individuals and organizations (e.g. all stakeholders in the nuclear community, including national regulatory authorities, nuclear power plant designers and operators, public interest organizations, the media, and local and national populations).

The structuring process in MCDA can contribute to increased coherence and consistency of the decision process by revealing the conflicting value systems and objectives of the actors involved (Roy, 1990). MCDA makes explicit that in the presence of conflicting objectives, the search for a global optimum is replaced by the search of a satisfactory compromise solution. Gamper and Turcanu (2007) argue that MCDA is a particularly suitable as a conflict solving tool as it allows for inter-comparison of options based on affected parties' interests and a structured decision process allowing to construct efficient solutions.
Furthermore, Munda (2019) suggests the use of an equity impact matrix *"illuminating all the distributional consequences of each single option on the various social actors"*.

Furthermore, the analysis of past experiences with NORM situations highlighted several (sources of) uncertainties (Guillevic et al ; pp. 107-110). While MCDA cannot address all of these, it may support managing the following sources of uncertainties:

- Choice of remediation strategy based on the site characterisation, environmental and dose impact assessment;

MCDA offers a tool able to cope with conflicting objectives, either by weighting the different evaluation criteria and deriving an overall ranking of remediation options.

- Achieving / maintaining remediation goals
- Uncertainties in the costs of the remediation

MCDA can take into account the uncertainty in achieving the goals of the remediation processes in various ways, for instance, through the use of scenarios and the derivation of robust strategies; the use of expected values, provided that probabilities for the various outcomes can be estimated; the application of uncertainty analysis to study the changes in the overall ranking depending on the variation of the scores of the different remediation strategies; the use of preference and indifference thresholds.

- Remediation of cultural heritage sites that have a cultural or religious significance which would be affected by remediation
- Long-term stewardship
- Remediation impact on the socio-economic development of region (non-radiological criteria may become the driving factors of decision-making)
- Health impact of remediation works

- Protection of vulnerable societal groups;

These can be supported by inclusion of related concerns as criteria in the evaluation of remediation options, with transparent and inclusive evaluation of options. Munda (2019) argues that the evaluation process should be "*as participative and as transparent as possible*"

- Who will pay the costs of remediation

This uncertainty can be addressed partly by breaking down the costs depending on who will bear these costs, with the inclusion of then preferences of respective stakeholders in the evaluation model. Additionally, the decision should take an integrated approach following the whole environmental management cycle (including for instance waste disposal and long-term stewardship).

- Availability of funds

Constraints can be specified for various criteria to rule out (possibly temporarily) remediation options that are unfeasible.

- Ethical uncertainties related to cost/benefit analysis

MCDA goes broader than CBA, as explained in the previous sections, in that it does not require conversion of all criteria to a common, monetary scale. This can address some of the ethical issues arising e.g. from converting potential health effects into costs (e.g. by setting a monetary value for the person*Sievert).

- Lack of consensus on the choice of a remediation

An iterative MCDA process may help in reaching a satisfactory compromise solution (see also previous point relating to conflict resolution).

- Lack of transparency.

MCDA promotes transparency in the decision-making process, including a clear problem structuring and detailed specification of the factors taken into account into decision-making. However, as mentioned earlier, a balance has to be sought between the complexity and the clarity of the MCDA model. In practical applications (see next section) it has been argued that the MCDA evaluation table my prove too technical and difficult to understand for non-experts.

- Uncertainties caused by limited technical knowledge of general population and other stakeholders and low understanding of the remediation issues and processes;
- Uncertainties related to a lack of trust between stakeholders in the remediation process;

MCDA may also be regarded as a learning process through which decision makers and stakeholders learn about the environmental remediation problem and ways to address the desired objectives. Highlighting the different points of view and clarifying the basis for decision-making, may also lead to trust building between stakeholders.

- Uncertainties related to different demands and concerns between stakeholders;

See point before, related to conflict resolution.

- Uncertainties resulting from little recognition of the links between environmental, economic, and social concerns of the stakeholders;

The problem structuring step can be used to identify all key concerns and building a consistent set of evaluation criteria.

- Uncertainties triggered by poor stakeholder involvement;

As mentioned before, MCDA has to provide opportunities for stakeholder engagement in decisions on the main elements of the method (remediation alternatives, evaluation criteria, etc). Moreover, it should clarify how decision will be taken on these elements and particularly on the role of MCDA in the decision making process.

2. Multi-criteria decision procedure for site remediation strategy, associated uncertainties and stakeholder involvement: case-study of the Belgian NORM site

From 1920 to 2013, phosphate ore processing was an important activity of the Tessenderlo group in Belgium. Phosphate ores were converted into dicalcium phosphates to be used as additive in fertilizers and animal feed. These industrial activities have generated large amounts of NORM waste, predominantly CaF2 sludge, disposed of in several dumping sites. A volume of 10 million m^3 sludge has been disposed in several dumping sites, covering a total area of approximately 81 ha. Remediation works have been started a while ago and will be on going for at least the next decade. The site considered as case study is currently remediated. The site contains, both radioactive and chemical pollutants and this mixed contamination is considered in the impact assessment and the remediation strategy. Based on the site characterization, OVAM (Flemish agency responsible for non-radiological waste and soil remediation) decided that there was a need for remediation and asked advice from FANC (Federal Agency of Nuclear Control) for the radiological part. The goal of the remediation action is to comply with the current legislation by decreasing contaminant concentrations in the solid phase of the site so that it can be classified as ‘natural reserve’.

The appropriate remediation strategy has been chosen by a soil expert following OVAM’s standard procedure for a soil remediation project (OVAM, 2018). Based on the site characteristics, legislation, best available techniques and expert judgement, the soil expert pre-selects relevant remediation strategies for the specific contamination scenario. Subsequently, the preferred option is selected based on a multi-criteria decision analysis (MDCA) considering the local and regional/global environmental aspects, technical and societal aspects and financial aspects. More details about the site characterization, the preselected remediation options and the selection procedure for the preferred remedial option can be found in Annex. More details about the MCDA process are given below.

2.1 Multi-criteria decision analysis

Within the multi-criteria decision analysis, the remediation options will be compared based on different criteria within the three different aspect groups. The meaning of each criterion within the three aspect groups is summarized in Table 2.

Table 2 Meaning of the used criteria within the multi-criteria decision analysis

Criterion	Explanation
Environmental aspects	
Reaching goals soil	Evaluation of the level of remediation that can be reached for the soil with the different techniques as stated in the soil remediation decree (i.e. limitations in use after remediation, removal of the risk, remediation to soil remediation standards, remediation to indicative values).
Reaching goals groundwater	Evaluation of the level of remediation that can be reached for the groundwater with the different techniques as stated in the soil remediation decree (i.e. limitations in use after remediation, removal of the risk, maximisation of soil remediation standards, remediation to indicative values).
Overall reduction pollution	Evaluation of the reduction of the pollution. This can be calculated based on the initial amount of polluted material and the expected results.
Limitations land use	Indication of limitations in land use after remediation measures were taken based on the expected results of the techniques.
Use secondary materials	Evaluation of the energy and extra materials will be necessary to implement the remediation strategy (e.g. covering foil, etc.). CO_2 emissions are also taken into account.
Direct emissions environment	Evaluation if the technique causes an impact towards another environmental compartment such as emissions to surface water, emissions to the sewer and emissions to the air. Within the evaluation, the number of impacted environmental compartments has to be taken into account together with the load and duration of the impact.
Other environmental burdens	Evaluation of other environmental burdens related to noise, smell, temperature, vibrations, environmental value, etc.
Time frame	The time it will take to remediate the site when using the different remediation techniques.
Technical and societal aspects	
Safety personnel	Evaluation of the risk for the personnel when working on the site. The possibility for contact with dangerous materials (including radioactive contaminants) is taken into account but also dangerous emissions, explosion danger, etc.
Effective damage	Indication of damage that is foreseen/expected within the remediation options such as demolishing specific infrastructures, damaging nearby private property (e.g. gardens).
Potential damage	This includes the risks related to the remediation techniques such as damage related to vibrations, explosions, etc. This criterion comprises potential damage that might be caused due to the works.
Safety measures	The necessary measures that need to be taken to guarantee the safety during remediation works (e.g. no access for unauthorized persons, no residential use of the site, safety measures to protect the workers against risks related to emissions, dangerous products, explosion, etc.).

Financial aspects	
Remediation costs	This includes all the costs related to the remediation technique. This can also include costs to restore effective damage and insurance costs for potential damage. There might also be costs related to the (temporary) delocalisation of neighbouring people. Also the costs related to a loss of exploitation can be taken into account.
Cost of remaining contamination	The remaining contamination at the site might be excavated in the future leading to an extra cost at that moment. These costs can be estimated based on the remaining contamination.

For each criterion within an aspect group, a score will be given for the different remediation options knowing that the maximum score can be 9 and the minimum score 1. The number of scores that can be divided between the different options within one criterion is the average of the score range ((1+9)/2=5) multiplied with the number of options (3 options x 5 = 15). So for each criterion, 15 scores can be divided between the three retained options. To attribute the scores, there are several (mathematical) rules available within the standard procedure for soil remediation (OVAM, 2018). Subsequently, the scores are multiplied with the weight of each criterion and summed to come to a final score.

To determine the weight of an aspect group and the criterions within these groups, guidelines are provided (OVAM, 2018). It is stated to give the 4 aspect groups, i.e. local environmental aspects, regional/global environmental aspects, technical and societal aspects and financial aspects, a weight of 33/12/22/33. To make this distribution, several stakeholders were consulted. For the NORM site, the weights were adapted; the local/regional/global environmental aspects considered in the environmental aspects group received a weight of 34 and the technical aspect group received a weight of 33. In addition, the financial aspect group received a weight of 33. As no two sites are equal, it is allowed in the OVAM guidelines to deviate from the prescribed distribution of the weights when it is motivated and especially in case of an urgent remediation need when there is a severe health or environmental impact risk or when there is a high safety risk related to the works.

Within the aspect groups, an equal weight was attributed to the different criterions. In the standard procedure for soil remediation, it is stated that the evaluation should be as objective as possible. As it is not possible to attribute different weights to the criterions in an objective manner, the weights should be equally distributed. Exceptions on this rule are the regional/global aspects group and the financial aspects group. For the financial aspects group, according to the OVAM guidelines, 2/3 of the weight was given to the “remediation costs” as the costs have a high impact on the selection of the remediation technique.

In *Table* 3, an overview is given on how the different criteria were evaluated for the three selected remediation options. The scores and weights are summarized in Table 4.

Option 2 received the highest score within the multi-criteria decision analysis and comes forward as the preferred remediation option.

Table 3 Comparison of different remediation options according to the criteria in the multi-criteria decision analysis

Criterion	**Option 1 – Excavation and off-site deposit**	**Option 2 – Excavation and on-site storage**	**Option 3 – isolation with top layer**
Environmental aspects			
Reaching goals soil	Complete remediation as all contaminated material is removed from 3 locations.	Partial removal of contaminated material: removal of contaminated material from 2 locations and controlled disposal at 1 location.	No removal of contaminated material but isolation at 3 locations.
➔	*Highest score*	*Intermediate score*	*Lowest score*
Reaching goals groundwater	Not applicable as project only for solid phase.	Not applicable as project only for solid phase.	Not applicable as project only for solid phase.
➔	*All options receive the same score*		
Overall reduction pollution	High reduction of the pollution.	Partial reduction of the pollution.	No reduction of the pollution.
➔	*Highest score*	*Intermediate score*	*Lowest score*
Limitations land use	No limitations in future land use but the use of the limited capacity of another waste deposit is negatively evaluated.	Installation of a cover and limitations in future land use for one site (sludge heap). On this site an extra capacity of 1.500.000 m^3 is realized resulting in an optimal use of the available space. No restrictions for future land use for the two other sites.	Installation of covers on the three sites and limitations in future land use to safeguard these covers.
➔	*Highest score*	*Intermediate score*	*Lowest score*
Use secondary materials	High energy consumption to excavate, load and transport waste, sludge and contaminated soil. Estimated CO_2 emission: 9282 ton CO_2	Less energy consumption compared to option 1 as the sludge will not be excavated. Materials and energy needed for drainage and installation of cover at one site. Estimated CO_2 emission: 3142 ton CO_2	No excavation but materials and energy needed for drainage and installation of covers at three sites. Estimated CO_2 emission: 314 ton CO_2
➔	*Lowest score*	*Highest score*	*Highest score*
Direct emissions environment	Highest emission to air of dust and greenhouse gasses. Emissions of drainage water and water related to excavation works to surface water.	Intermediate emission to air of dust and greenhouse gasses. Emissions of drainage water and water related to excavation works to surface water.	Least emission to air of dust and greenhouse gasses. Emissions of drainage water to surface water.
➔	*Lowest score*	*Highest score*	*Highest score*

Other environmental burdens ➔	Noise pollution related to excavation and transport of waste. *Lowest score*	Noise pollution related to excavation, transport of waste and materials for the top layer on the sludge heap. Impact on natural value for one site as no deep-rooted vegetation can be grown on the covering layer. *Score slightly lower than option 3*	Noise pollution related to transport of materials for the top layers on the three sites. Impact on natural value for the three sites as no deep-rooted vegetation can be grown on the covering layers. *Highest score*
Time frame ➔	> 5 years *All options receive the same score*	> 5 years	> 5 years
Technical and societal aspects			
Safety personnel ➔	Excavation of the largest volume of contaminated material resulting in the highest risk for direct contact. *Lowest score*	Excavation of a large (but less than option 1) volume of contaminated material resulting in a high risk for direct contact. Installation of a top layer also creates a risk of exposure to contaminated material. *Intermediate score*	Installation of a top layer creates a risk of exposure to contaminated material. *Highest score*
Effective damage ➔	Not applicable *All options receive the same score*	Not applicable	Not applicable
Potential damage ➔	No potential damage is expected. *Highest score*	Risk related to the stability of the underground when installing a waste deposit and cover. *Intermediate score*	Highest risk related to the stability of the underground as the material will not be excavated or dewatered. *Lowest score*
Safety measurements ➔	High need for safety measures due to excavation and transport via public roads. *Lowest score*	Safety measures needed due to excavation works and installation cover. *Intermediate score*	Safety measures needed due to installation covers. *Highest score*
Financial aspects			
*Remediation costs** ➔	41.26 MEuro *Lowest score*	12.93 MEuro *Highest score*	20.22 MEuro *Intermediate score*
Value remaining contamination ➔	No remaining contamination. *Highest score*	Contamination on 1 site. *Intermediate score*	Contamination on 3 sites. *Lowest score*

*A detailed calculation of the remediation costs can be found in Annex

Table 4 Weights and scores attributed within the multi-criteria decision analysis

Criterion	Weight	Option 1 – Excavation and off-site deposit	Option 2 – Excavation and on-site storage	Option 3 – isolation with top layer
Environmental aspects				
Reaching goals soil	4.25	9.0	5.0	1.0
Reaching goals groundwater	4.25	5.0	5.0	5.0
Overall reduction pollution	4.25	9.0	5.0	1.0
Limitations land use	4.25	7.5	6.5	1.0
Use secondary materials	4.25	2.9	6.1	6.0
Direct emissions environment	4.25	3.0	6.0	6.0
Other environmental burdens	4.25	2.5	6.0	6.5
Time frame	4.25	5.0	5.0	5.0
Subtotal	*34*	*186.6*	*189.6*	*133.9*
Technical and societal aspects				
Safety personnel	8.25	3.0	5.5	6.5
Effective damage	8.25	5.0	5.0	5.0
Potential damage	8.25	6.5	4.5	4.0
Safety measurements	8.25	2.0	6.0	7.0
Subtotal	*33*	*136.1*	*173.3*	*185.6*
Financial aspects				
*Remediation costs**	22	3.5	6.0	5.5
Value remaining contamination	11	9.0	5.0	1.0
Subtotal	*33*	*176.2*	*185.7*	*132.9*
Total	**100**	**498.9**	**548.5**	**452.4**

* See Annex or the calculation of the scores related to remediation costs

2.2 Conclusion and reflection on uncertainties and stakeholder involvement

To select the most favorable remediation technique, evaluation criteria related to environmental, technical, societal and financial aspects were taken into account. Although it was intended to make the evaluation and selection as objective as practically feasible, **uncertainties** can be related to, for example:

- The sampling and measurement campaign to map the contamination problem and decide on the remediation necessity
- The final result of the remediation (e.g. will there be some contamination left after excavation works, will there be contamination left due to leaching over the past years, etc.)
- The cost of the project
- The time the remediation works will take
- The sustainability of the remediation option (e.g. what will the situation be within 100 years, it should be monitored, etc.)
- Expert judgement for pre-selection of the best remediation techniques
- Selection of the criteria and attribution of the weights and scores in the multi-criteria decision analysis

To define the remediation need and select an appropriate remediation option, different **stakeholders** were involved, i.e. the company responsible for the contamination, the Flemish governmental agency responsible for non-radiological soil pollution (OVAM) and the Federal regulator of nuclear activities (FANC). It can be concluded that very detailed procedures are available to decide on the remediation need and to select a soil remediation strategy. Multiple supporting studies are required that need to be provided by independent experts (e.g. human and environmental impact studies, on site sampling and measuring, defining counter measures to limit environmental impact and burden to the public). When suggestion remediation options, putting forward counter measures and making decisions, the Flemish and Belgian legislative framework should be taken into account. As such it is aimed to make the selection of a remediation technique in an informed and objective way. Once a remediation system has been selected, a health, safety and environmental care system has to be set up according to specific guidelines (OVAM, 2017). In these guidelines, communication towards the stakeholders (e.g. media, public, etc.) is included.

2.3 Focus group discussion on the application of MCDA for decision making on site remediation

The practical application of MCDA was also addressed in a stakeholder panel organized in the framework of the TERRITORIES project on March 18, 2019.

The main findings are summarized below:

- Choice of MCDA for the regulatory framework
  - Prior to 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
  - CBA is considered as “not ideal”; one participant argued that finding the best option from both a financial and risk avoidance point of view is not only a matter of costs and benefits;
  - The switch to the use of MCDA for soil remediation was a gradual process, it is the result of a 20 years process; MCDA was found “extremely suitable” and “by far the best way” to identify and include the different factors (e.g. financial, technical, radiological, acceptability) into decision making.
  - MCDA helps highlight that some options are not socially responsible, e.g. removing and transporting large amounts of contaminated soil;
- Evaluation criteria
  - The set of criteria evolved throughout the years, they can be used to reflect the “spirit of the time” in the decision-making process; for instance nowadays the environmental impact is an important factor but it was not so in the past. The calculation of CO2 emissions was for instance included in the MCDA methodology very recently; this criterion is questioned by one participant who suggested that the km of transport necessary and the number of vehicles could be used instead. Another participant suggested that the hindrance created by the remediation work is also important.
  - Social factors are also indicated as important, for instance return to a remediated area after a nuclear accident is not a scientific or technical problem but a social one. Perception of radioactivity may differ from that of heavy metals.

- Participants mentioned that for the remediation work for the Belgian sites, there was anxiety among the local residents more related to the practical aspects, e.g. what do the remediation works consist of?
- The financial aspects are very important, but may not be seen as such by all stakeholders (e.g. in the MCDA methodology they have a weight of 0.3);

- Evaluation of MCDA as a decision-aid tool
  - Experts have to use the prescribed method and there is little room to deviate from this; for instance, when the quantification method of criteria is prescribed it has to be applied as such;
  - MCDA is recognized as good for bringing all the factors into evaluation, as means to support the decision, not to take a decision; participants argued that “in the end, you always have to use common sense” and that “MCDA is rather a formalism to frame the expert judgment”.
  - Establishing criteria weights is always a difficult point, as they introduce subjectivity in the evaluation;
  - MCDA acts, according to one participant as “a translation of a the regulatory process and an assessment process that you as an expert make to come to the best decision for a certain project”.
  - MCDA helps comparing alternatives and position them with respect to each other; there is always an implicit MCDA necessary, although not necessarily specifying criteria weights (“MCDA light”).
  - One participant noted that in a case when the health impact would be higher, decisions (including the use of MCDA) balancing the different factors would have been more difficult.
  - Uncertainties linked to a project and the time duration taken into account for predictions complicates the use of MCDA, as “it is more difficult to put this in a table”.
- Participation
  - Some participants argued that it is difficult to include stakeholders in the process of establishing criteria weights, as this requires a lot of technical knowledge that “goes beyond personal interests”;
  - The decision problem is seen by participants as the responsibility of the expert responsibility, although consultation and suggestions from stakeholders should be taken into account.
  - The use of MCDA is seen as more practical as an expert tool.
- Transparency of the decision process using MCDA
  - MCDA (the evaluation table) is considered by one participant as too technical to be communicated to non-experts, who argued that it is easier to explain the choice of an alternative using “+” and “-“; chosen because it is so and so cheaper", so you can use aspects, but the table is too technical;
  - The underlying reasoning is deemed however easier to be explain (e.g. the criteria).
- Suggestions to facilitate the use of MCDA
  - Most participants suggest to apply the MCDA process but without giving numerical weights to criteria.

3. Conclusions

MCDA provides a promising paradigm since it can stimulate a “good decision making process” (Keeney and Raiffa, 1976) by:

- Clearer illustration of the different inputs that go into decision-making.
- Inclusion of all relevant aspects, without forcing them to a common, e.g. monetary scale.
- Transparency, traceability and consistency of decisions.

The field of MCDA is still under-developed for environmental remediation in the context of NORM and post-accident management. However, lessons can be learned from experience in connected, non-nuclear fields, e.g. soil remediation or environmental management. MCDA methods have been included in some legal guidelines and practitioners argue that this is “by far the best way” to identify and include the different factors (e.g. financial, technical, radiological, acceptability) into decision making.

MCDA is seen both by scholars and practitioners as a decision-aid, rather than a decision-making tool. Even if the details of the MCDA methods may be difficult to explain to the wider publics, the underlying reasoning (e.g. the evaluation criteria) could be used as an aid for communication, particularly when supported by visuals.

While MCDA is well suited for integration within participatory processes for decision-making on environmental issues, it should in turn integrate stakeholder participation in decisions on the main elements of the process, clarifying how these decisions will be taken. Moreover, the role of the multi-criteria decision analysis in the decision process should be clearly established from the outset of the analysis (Van den Hove, 2006).

Further work on the application of MCDA for environmental remediation should pay due attention to the inclusion of stakeholder engagement considerations in and with MCDA, broadening the scope of social criteria beyond the generic and over-simplified “stakeholder acceptance” or “stakeholder perception” which can be encountered in a large number of case studies in the literature, the design of methodologies addressing the entire cycle of environmental management of contaminated sites, provision of specific guidance for the assessment of social and economic impacts of environmental remediation, provision of guidance for inclusion of sustainable remediation considerations, improving the transparency of the underlying modelling process, and inclusion of uncertainty modelling in practical MCDA tools.

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Annex Decision procedure site remediation strategy, associated uncertainties and stakeholder involvement: case-study Belgian NORM site solid phase

1 Description of the site

The site of interest is related to the Belgian phosphate industry and encompasses three areas:

- The CaF2 sludge heap (1 on figure 1)
- The solid phase (soil and waste) of a wastewater basin (2, 3a and 3b on Figure 2)
- The solid phase (soil and waste) of the area called 'Spoorwegstraat' (5 on Figure 2)

On these areas, historical contamination with ^{226}Ra, heavy metals, mineral oil and poly-aromatic hydrocarbons has been identified in the solid phase (soil, sludge and waste). The site is related to the NORM-industry (i.e. industries that use raw materials that contain naturally occurring radionuclides and where enhanced levels of naturally occurring radionuclides can be present in residues due to the processing of these materials). In most NORM-contaminated sites, both radioactive and chemical contamination is present and this mixed contamination should be taken into account when performing an impact assessment and defining a remediation strategy.

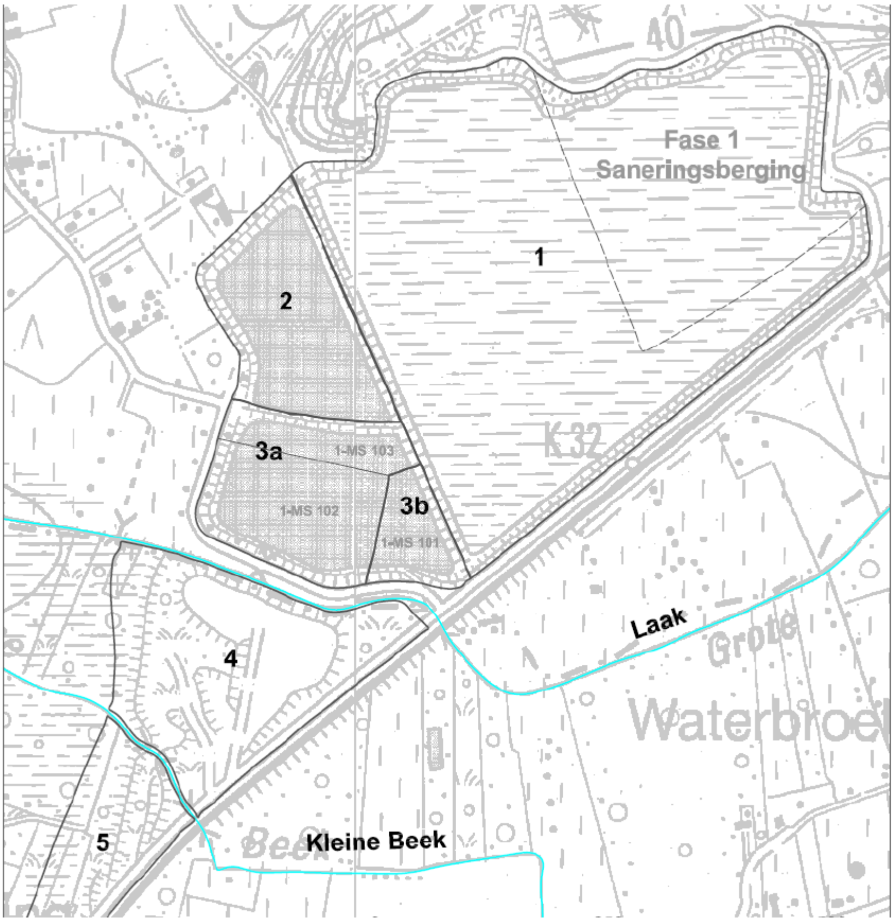

Figure 2 Map of the contaminated site with indication of the different areas

2 Site characterization and evaluation

To quantify the pollution and map the contamination problem, a sampling campaign was performed. Based on the information of the sampling campaign and the legislative framework (i.e. Flemish soil decree and implementing order), OVAM (Flemish agency responsible for waste and soil remediation)

decided that there is a need for remediation. In Belgium, OVAM deals with chemical pollution but asks advise from FANC (Federal Agency of Nuclear Control) for the radiological part. Soil remediation standards are available through the following links:
http://www.kustcodex.be/kustcodex-consult/plainWettekstServlet?wettekstId=33379&lang=nl

The goal of the remediation action is to comply with the current legislation by decreasing contaminant concentrations in the solid phase of the site so that it can be classified as 'natural reserve'.

3 Selection appropriate remediation strategy

3.1 Introduction

The selection of an appropriate remediation strategy is based on the guidance document "Standard procedure for a soil remediation project" from OVAM (OVAM, 2018). This document lists and explains the research and information necessary to define a soil remediation project. This work is done by a soil expert.

Based on (1) supporting information on the location and history of the site, contamination levels, legislation, etc. (3.2), (2) guidelines related to best available techniques (3.3), and (3) expert judgement, a soil expert pre-selects relevant remediation strategies for the specific contamination scenario (3.4). Subsequently, these pre-selected strategies are compared based on expected results, impact on humans and environment, future limitations of site use, financial situation, etc. (3.5). Finally, the preferred option is selected based on a multi-criteria analyses (3.5.5).

3.2 Supporting information

3.2.1 Location of the site

The site is located in Belgium in the province of Limburg.

Figure 3 Aerial view of the site

- The **CaF_2 sludge heap** (1 on figure 1) has a surface of approximately 26.3 ha. From a geographical point of view, the site is located in the 'Southern Kemps' and the embranchments of the 'Hageland'. The sludge heap is built against the southern side of a typical northeast-southwest orientated ridge ('Diestiaan hill') of the 'Hageland' called the 'Kepkensberg'. After industrial activities have ended and remediation measures have been implemented, the site will be classified as 'natural reserve'.

- The **wastewater basin** (2, 3a and 3b on figure 1) is on its eastern side adjacent to the sludge heap and is located in the valley of two local rivers. It has a surface of approximately 10 ha. After industrial activities have ended and remediation measures have been implemented, the site will be classified as 'natural reserve'.
- The **area 'Spoorwegstraat'** (5 on figure 1) is located south-west of the sludge heap and has a surface of a few ha. The area will be classified as 'natural reserve' after remediation measures are taken.

The site is located approximately 1.5 km north-east of the centre of a small town (~8000 inhabitants). The land adjacent to the site is classified as 'natural reserve' or 'agricultural land'. The area is drained by two small rivers that belong to the Scheldt basin. In addition, there is a canal 2 km north-east of the site. There is a swampy zone adjacent to the area 'Spoorwegstraat' and this zone is sensitive to flooding. Also the area south-east of the sludge heap is sensitive to flooding.

3.2.2 History of the site

3.2.2.1 Sludge heap

The sludge heap is built against the southern side of a typical northeast-southwest orientated ridge ('Diestiaan hill') of the 'Hageland'. The other sides are dikes up to 8.5 m composed of typical 'Diestiaan sands'. The western dike of the sludge heap is at the same time the eastern dike of the wastewater basin. The sludge heap consists of industrial sludge without a bottom-layer. Residues (CaF_2 sludge) from the phosphate facilities, in which phosphate ores are processed to be used in fodder and fertilizers, have been pumped onto the heap from 1930 until 1979. The phosphate ores contained ~70% $Ca_3(PO_4)_2$, $CaCO_3$, SiO_2, Al- and Fe-oxides, fluorides and trace levels of heavy metals such as As, Cd, Cr, Cu, Pb, Ti, Se, Sr, V, ^{238}U (with daughter ^{226}Ra) and Zn. The ores contained 1200-1500 Bq kg^{-1} ^{226}Ra. The CaF_2-sludge was formed during the production of $Ca(H_2PO_4)_2$ from $CaF_2.3[Ca_3(PO_4)_2]$ using HCl as the extractant. Reaction (1) gives the first step in the total production process. In this step the CaF_2-sludge was produced as waste product.

$$CaF_2.3[Ca_3(PO_4)_2] + 12\ HCl \rightarrow 3\ Ca(H_2PO_4)_2 + 6\ CaCl_2 + CaF_2 \qquad (1)$$

Since the beginning of the 1990's the procedure has been changed. In the new procedure $BaCl_2$ was added during the production process to precipitate Ra. Ninety percent of the Ra could be precipitated as radium sulfate which could be removed together with the barium sulfate precipitate. The sludge on the sludge heap dates from before this new procedure and is therefore less radioactive. At the end of 2013, the production of dicalcium phosphates stopped.

Leaching tests on the sludge indicate that only salts significantly leach out which might have influenced the groundwater in the first years as bottom-layers were not used. However slowly, by increasing the amount of sludge on the site, this leaching towards the groundwater decreased due to the low permeability of the sludge reinforced by the increased pressure. Infiltration of rainwater through the heap is limited by the excavated drainage canals. These canals drain rainwater and percolation water.

3.2.2.2 Wastewater basin

An important amount of $CaCl_2$ containing wastewater is discharged into local rivers. Already since the beginning of the 1930's there has been a separation between $CaCl_2$ containing wastewater and other water. Before discharging to the river, the wastewater was collected in a wastewater basin for sedimentation purposes and control of discharge rates. Several basins have been constructed over the years. In 1990, the use of the northern part of the wastewater basin (2 on figure 1) was stopped and the sediments were removed. Between 2010 and 2013, the use of the southern part (3a and 3b on figure 1) was stopped and the sediments removed. Since then, the wastewater basin is equipped with an impermeable layer at the bottom.

3.2.2.3 Area Spoorwegstraat

Area Spoorwegstraat is a small waste heap that contains approximately 50.000 m³ waste and CaF_2 sludge.

3.2.3 Geology and hydrology

The local geology, limited to the phreatic aquifer, consists mainly of glauconitic sands that contain more clay at the top and more glauconite at the bottom. Table 5 gives an overview of the different layers with their most important characteristics (until the Boom Clay layer).

Table 5 Overview of the different layers and their characteristics

Depth (m-sl)	Texture	Heterogeneity and stratification	Stratigraphy	Hydraulic conductivity Decimal (m/d)	Hydraulic conductivity Description	Organic matter (%)	Clay (%)	Remarks
0-few	Fine, loamy sand (Diestiaan hill) and clayey alluvium (valleys)		Quaternary	-	Moderate			
0-80	Green, clayey sand and clay, transition to coarse glauconitic sand at higher depth, iron sandstone		Tertiary Form. of Diest Member of Diest	6-14	Very good			
80-100/140*	Dark green, fine glauconitic sand		Tertiary Form. of Diest Member of Dessel	Max. 5	Good			
100/140-170	Grey, firm clay with septaria		Tertiary Form. of Boom (Boom Clay)	-	Almost not			Closure phreatic aquifer
The hydraulic conductivity was based on multiple pump tests in the region.								

* The top of the Boom clay can locally vary strongly in height due to an erosion channel through the clay and the slope of the adjacent sides of this 'valley'.

The complete package of Diestiaan sands can be considered as one phreatic aquifer. The groundwater table is situated at depths of maximum a few meters in the valleys and at higher depths of sometimes more than 10 m below surface level under the Diestiaan hills. The flow of the shallow groundwater is presented on a piezometric map that was put together based on measurements in different observation wells (Figure 4). The apparent increasing drainage towards the local streams is the effect of a drainage system under the wastewater basin. The direction and gradient of the flow of the deep ground water are comparable with these of the shallow groundwater. An important and expected difference between the shallow and deep groundwater is the draining effect of the streams and the influence of the drainage system under the wastewater basin (at higher depth no deviating isohypses). In addition, on the west side of the wastewater holding ponds, there are some variations due to the higher salt concentrations in some observation wells. The piezometric map for the deep groundwater was therefore put together based on measurements in observation wells that were not influenced by the salt. Figure 5 an Figure 6 show the piezometric maps for a larger area surrounding the site. As such an overview is given of the groundwater table based on the measured groundwater levels. For the deep groundwater no corrections towards a freshwater column were made. Generally, the orientation of the groundwater current over the complete depth of the aquifer is west-southwest.

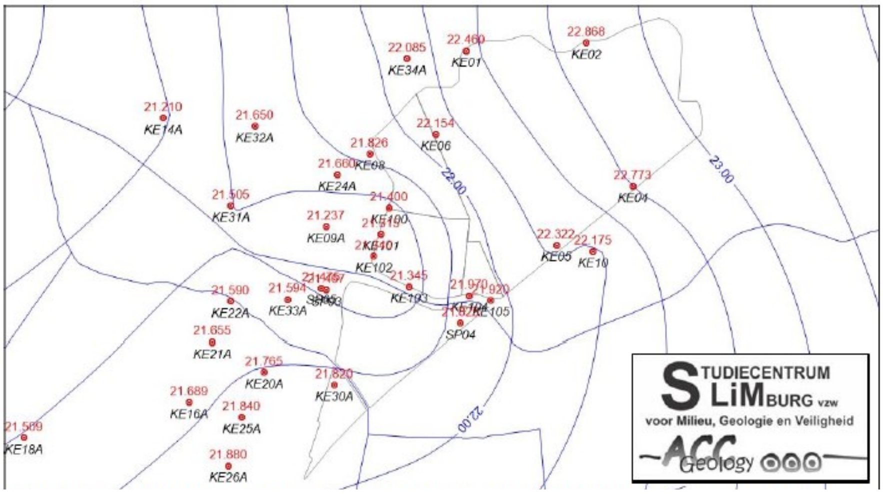

Figure 4 Piezometric map of shallow groundwater (measured 05/05/2013)

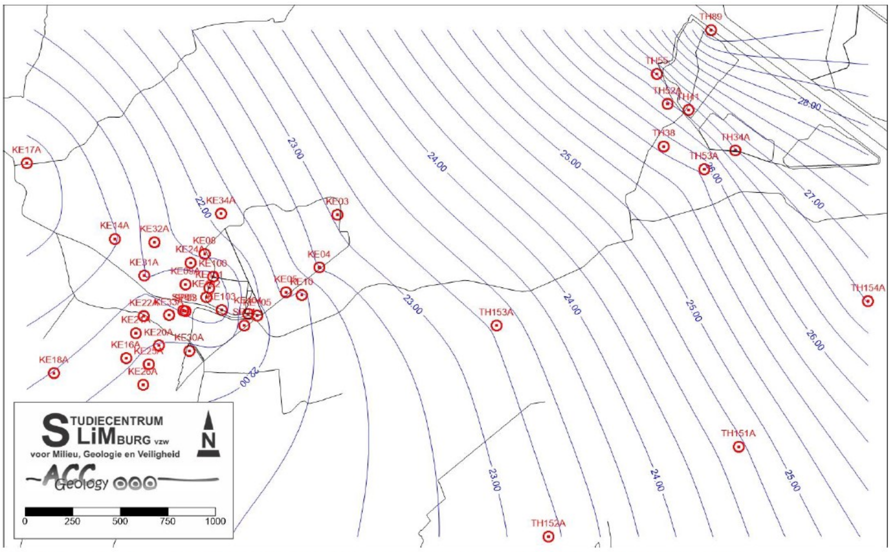

Figure 5 Piezometric map of shallow groundwater (0-15 m below surface level)

(measured 5/5/2013 and 11/5/2013)

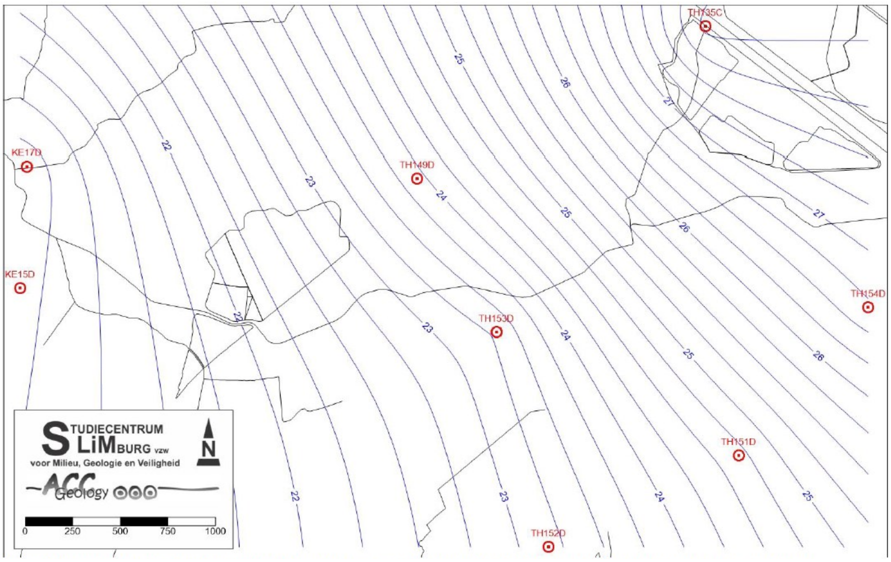

Figure 6 Piezometric map of deep groundwater (>90 m below surface level)

(measured 5/5/2013 and 11/5/2013)

3.2.4 Soil contamination

Between 1988 and 2013, 13 studies were performed to identify and map the contamination on the sludge heap and the wastewater basin. Concentrations of chlorides, sulphates, heavy metals, fluoride and ^{226}Ra were found that clearly indicate a severe soil contamination. For the area Spoorwegstraat, 3 studies were performed between 1988 and 2014 and a clear indication of severe soil contamination was found for chlorides, sulphates, heavy metals, mineral oil, Ba, poly-aromatic carbohydrates and radionuclides. Table 6 gives an overview of the contamination present on the site.

Table 6 Overview contamination present on the site

Area	**Medium**	**Type of contamination**
Sludge heap	Solid phase: CaF_2 sludge	Historical contamination with heavy metals such as As, Cd, Cr, Cu, Hg, Ni, Zn and ^{226}Ra
Wastewater basin	Solid phase: soil below sediments	Historical contamination with heavy metals and ^{226}Ra
Area Spoorwegstraat	Solid phase: waste, soil and sludge	Historical contamination with heavy metals, Ba, mineral oils, poly-aromatic carbohydrates and radionuclides

3.2.4.1 Sludge heap

The sludge is a residue from the phosphate industry and contains predominantly CaF_2. It is approximately 6 m thick and has a volume of approximately 1.200.000 m³. The sludge on the surface of the site is covered with vegetation and is contaminated with heavy metals and other contaminants such as Ra, U, Sr, etc. for which no legal limits exist. It is historical contamination related to the deposition of sludge between 1930 and the early '80s. Table 7 gives the measured metal content of sludge samples and the comparison with soil remediation standards for 'industrial area' and 'natural reserve' sites. In Table 8, the radionuclide concentrations in sludge and drainage water are presented. Dose rates of 360-850 nSv h^{-1} can be found in the areas that are not covered with another layer with local values up to 1150 nSv h^{-1}. Where the sludge has been covered by clean soil, dose rates of 120-280 nSv h^{-1} can be found. The Rn concentrations vary between 30 and 85 Bq m^{-3}.

Table 7 Metal concentrations in sludge [mg kg^{-1} Dry Mass] and comparison with soil remediation standards when the site is considered 'industrial area' or 'natural reserve'

Element	# samples	Average	Min.	Max.	SRS* 'industrial area'	# samples exceeding standard	SRS* 'natural reserve'	# samples exceeding standard
As	19	22.7	5	85	267	0	58	2
Cd	19	38.2	2	87.7	30	11	4.38	15
Cr (III)	17	1197.6	350	1971	880	13	130	17
Cu	14	98.8	54.6	170	500	0	137.62	1
Hg	13	17.4	1	56	11	8	2.9	12
Pb	19	54.5	10	105	1250	0	200	0
Ni	12	81.1	32	120	530	0	93	6
Zn	19	701.4	190	1400	1250	1	407.16	16

*SRS = soil remediation standard

Table 8 Radionuclide concentrations for the sludge and drainage water

Sample number	^{210}Pb	^{226}Ra	^{238}U	^{210}Po
Drainage water [Bq L^{-1}]				
1	0.62 ± 0.07	0.357 ± 0.022	0.056 ± 0.011	0.087 ± 0.012
2	< 0.09	0.026 ± 0.003	0.031 ± 0.006	0.051 ± 0.008
3	0.48 ± 0.12	0.47 ± 0.05	0.038 ± 0.002	0.069 ± 0.010
Sludge [Bg kg^{-1}]				
1	1700 ± 1400	1080 ± 60	7400 ± 900	2300 ± 400
2	1900 ± 1500	1430 ± 80	8000 ± 1000	2700 ± 500
3	3500 ± 2800	4240 ± 220	5900 ± 800	4100 ± 700

Leaching tests indicate that only the salts leach out significantly from the sludge although the limiting values are not exceeded (Table 9). Therefore no increased values for other contaminants (except for the salts) are expected in the soil underneath the sludge. Soil samples were analysed in the vicinity of another sludge heap nearby where similar sludge has been deposited and no concentrations above the soil remediation standards were detected.

Table 9 Leaching results [mg L^{-1}] for the sludge

	*Limiting value**	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
pH	*4-13*	6.85	7.48	7.35	7.14	7.37	7.55
F^-	*50*	6.5	7.1	6.6	6.8	6.8	6.8
SO_4^{2-}	*5000*	493	396	406	379	386	448
Cl^-	*10000*	65	80	194	65	110	136.5
CN^-	*1.0*	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
NO_2^-	*30*	<0.01	0.012	0.011	<0.01	0.040	<0.01
NH_4^+	*1000*	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
As	*1.0*	<<1	<<1	<<1	<<1	<<1	<<1
Cd	*0.5*	<<0.005	<<0.005	<<0.005	<<0.005	<<0.005	<<0.005
Cr	*0.5*	<<0.01	<<0.01	<<0.01	<<0.01	<<0.01	<<0.01
Cu	*10*	<<0.1	<<0.1	<<0.1	<<0.1	<<0.1	<<0.1
Hg	*0.1*	<<1	<<1	<<1	<<1	<<1	<<1
Ni	*2.0*	0.054	0.059	<<0.05	<<0.05	<<0.05	<<0.05
Pb	*2.0*	<<0.05	<<0.05	<<0.05	<<0.05	<<0.05	<<0.05
Zn	*10*	0.022	0.010	0.008	0.011	<<0.01	0.010
Fenols	*100*	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

*According to Flemish legislation

From the human risk evaluation, it is concluded that the NORM site does not pose an actual toxicological risk. The measurements indicate that there is no actual or potential risk for further dispersion of the contaminants. The presence of heavy metals in the surface layer of the CaF_2 sludge does not pose an eco-toxicological risk as long as the site is used as sludge heap. However there is a potential toxicological risk from the heavy metals in the sludge when the area would become natural reserve.

Also with respect to the radiological risk, the impact towards the public and environment is negligible at this moment as the site is not publically accessible. For persons working on the site, there is a risk from external exposure and inhalation of dust and Rn. Spending 1000 hours per year on the landfill will result in an average external dose of about 0.6 mSv y^{-1} and, considering an average Rn concentration of 50 Bq m^{-3} in air, the Rn inhalation dose will be approximately 0.5 mSv y^{-1} (Vanmarcke et al., 1993). Also from the revised dose impact made by Sweeck (2014) for a similar waste heap, it is expected that exposure due to leaching and dispersion of radionuclides via the groundwater will be significantly smaller than the dose limit of 1 mSv y^{-1}.

3.2.4.2 Wastewater basin

There is historical contamination of the natural soil present underneath the wastewater basin. It concerns soil contaminated with heavy metals such as Cd. In Table 10, metal and radionuclide concentrations in several soil samples are presented and compared to the soil remediation standards.

The volume contaminated soil was estimated to be 150.000 m³.

Due to its current contamination levels, the soil cannot be used as topsoil when the area will be converted into natural reserve.

Table 10 Metal and radionuclide concentrations [mg kg^{-1} dry mass] in soil samples of the wastewater basin

Element	**Sample 1**				**Sample 2**				***SRS[a]***
	0-0.5 m depth	*0.5-1 m depth*	*1-1.5 m depth*	*1.5-2 m depth*	*0-0.5 m depth*	*0.5-1 m depth*	*1-1.5 m depth*	*1.5-2 m depth*	
As	40	<10	15	20	<10	13	20	20	*70*
Cd	5.5	2.4	1.9	2.5	1.1	4.4	2.6	2.3	*4.4*
Cr	70	51	96	100	52	73	110	100	*130*
Cu	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	*180*
Hg	0.13	<0.10	0.39	<0.10	<0.10	<0.10	<0.10	<0.10	*2.9*
Ni	16	9	11	14	7.6	32	16	17	*93*
Pb	11	<10	<10	10	<10	<10	<10	<10	*200*
Se	3.7	5.8	2.9	2.2	7.9	3.2	2.3	2.7	-
V	80	56	110	110	57	80	120	110	-
Zn	41	25	37	43	19	55	36	35	*601*
Ra[b]	770	310	480	190	120	320	490	400	-
U	<1	<1	1.0	1.7	<1	1.4	1.2	1.6	-

[a]SRS = soil remediation standard

[b]Ra concentration is expressed as [Bq kg^{-1} Dry Mass]

3.2.4.3 Area Spoorwegstraat

Contamination was found in the waste and natural soil underneath the waste in de the area Spoorwegstraat. The identified contamination included heavy metals, mineral oil, poly-aromatic carbohydrates, Ba and radionuclides such as ^{226}Ra. Table 11gives the metal concentrations in several waste/soil samples and the comparison with soil remediation standards when the site is considered 'industrial area'.

Table 11 Metal concentrations in soil/waste [mg kg^{-1} Dry Mass] and comparison with soil remediation standards when the site is considered 'industrial area'

Element	# samples	Average	Min.	Max.	SRS* 'industrial area'	# samples exceeding standard
As	30	82.9	4	580	267	3
Cd	30	86.0	0.4	1200	30	13
Cr (III)	30	207.5	15	1200	880	2
Cu	30	86.11	5	530	500	1
Hg	30	688.6	0.1	16000	11	6
Pb	30	613.1	13	7900	1250	3
Ni	30	29.6	3	91	530	0
Zn	30	3435.3	20	78000	1250	7

The waste is not covered. As the site is fenced, there is no actual toxicological risk for humans. When the area would finally become natural reserve (as planned within several hundreds of years), there can be a potential toxicological risk as the site would become free accessible and humans could come into contact with some parts of the waste. The underlying soil (underneath the waste) is affected by the contaminants (although only limited effects could be determined). For example, the eco-toxicological risk value for Cd was exceeded. As such, there remains an eco-toxicological risk, even after removal of the waste.

As the material has been deposited on the site since decades, it can be assumed that the lowest sludge layer is compressed and leaching will no longer occur. An equilibrium has been reached between the concentration in the solid phase and the groundwater. There are no indications that the contamination level of the groundwater will increase due to leaching of contaminants from the waste or the soil.

3.2.5 Specific legislation

On the sludge heap and area Spoorwegstraat, vegetation is present including different types of trees. A licence has to be requested to the authorities to remove the trees if required in the remediation strategy.

3.2.6 Technical aspects

The sluice that is present on the sludge heap has no function anymore and will have to be removed. On several locations related to the wastewater basin and area Spoorwegstraat, fences and dikes will have to be removed and two small bridges over two local rivers will be removed and subsequently replaced by new ones.

Several pipes are present on the sludge heap for the removal of drainage water which is transported to a wastewater cleaning facility. Some of the pipes on the site that are out of use will be removed. Several other pipes and cables are located on the sites and plans are available on which the exact locations are indicated. Near these pipes, traffic of heavy trucks has to be avoided at all times.

The nearest house is located approximately 200 m north of the wastewater basin. This needs to be taken into account with respect to noise and smell.

In the near vicinity, there is a local river in which most of the water related to the site will be disposed after treatment in a wastewater cleaning facility and buffering in a wastewater basin.

On the area Spoorwegstraat, waste has been deposited up to a height of 8 m above the surrounding field. The stability of the site has to be taken into account when working there. A certain slope has to be taken into account during excavation works to ensure no material will slide off. It should be ensured that nobody is present at the foot of the hill during the works. The same remark is applicable for the removal of the dikes present at the wastewater basin.

The sludge heap and the wastewater basin are accessible for large/heavy machines (e.g. bulldozers, trucks, etc.). As the southern part of the wastewater basin will be active for several years, at this moment this area is not accessible for heavy machines due to the pipes present on the site. After the industrial activities have ended and the site will be remediated and converted into natural reserve, this area is accessible for these machines.

The concentration ^{226}Ra in the CaF_2 sludge is much higher than the clearance levels for radioactive material (i.e. 0.01 kBq kg^{-1}). Therefore, the sludge cannot be valorised in building materials. Recuperation of fluoride is economically not feasible as was shown by a separate study.

If groundwater has to be extracted, the concentration of the contaminants has to be determined and if necessary the water has to be remediated before discharging it into the river.

As the area Spoorwegstraat and the wastewater basin contain glauconite-containing sands, several practical limitations of working with these sands have to be taken into account. First, it should be taken into account that it can be very difficult to drive a vehicle over these sands, especially when it is raining. Second, it is practically not feasible to condense these sands. During condensation, the grains will break, increasing the fraction of fine particles.

A study has been performed to determine the geotechnical behaviour of the CaF_2 sludge to see if it can be used as material to build dikes. Extensive laboratory tests were performed and similarities and differences were found compared to soil. Therefore test dikes were built to evaluate actual behaviour of the material. In addition, computer simulations were performed and the model was calibrated with measurements from the test dike. It can be concluded that dewatered material can be used as building material for dikes when taken into account several precautions such as building with a certain slope and ensuring sufficient drainage.

3.3 Best available remediation techniques

There are Flemish guidelines for pre-selection of relevant techniques to remediate contaminated soil (Goovaerts et al., 2006). These guidelines were made within the project BBT/EMIS of the Flemish region initiated by the ministers for Research policy and for Environment, The Flemish Administrations Environment (AMINAL) and Economics and the Flemish Institute for Technological Research (VITO). Industry and government (IWT, OVAM, VLM, VMM) were consulted for scientific support and guidance.

For the different techniques, information is provided on the principle of the technique, the area of application, the costs and the environmental burden and possible countermeasures to reduce waste and emissions towards different environmental compartments.

It is not our intention to provide a complete overview of all the available soil remediation techniques but in general there are three possible remediation techniques:

- *Immobilisation* to reduce the leachability or bioavailability of the pollutants without removing them from the soil.
- *Isolation* of the contaminated soil from the rest of the environment to prevent further dispersion or exposure of humans and non-human biota.
- *Removal* of the pollutants from the soil with different techniques such as physico-chemical techniques (e.g. chemical oxidation), biological techniques (e.g. phytoremediation) and civil-technical techniques (e.g. excavation).

3.4 Selection of relevant soil remediation strategies

Based on the information in the guidance document (Goovaerts et al., 2006) and the supporting information (section 3.2), a soil expert made an informed decision and pre-selected the following remediation strategies for the NORM site:

- Excavation and off-site storage
- Excavation and on-site storage
- In-situ immobilisation
- Isolation using a horizontal top layer

3.5 Comparison of relevant soil remediation strategies

3.5.1 Description remediation options

3.5.1.1 Excavation and off-site storage

- Approximately 1.500.000 m³ material (soil, sludge, waste) contaminated with heavy metals and radionuclides needs to be excavated.
- Excavation of soil under the groundwater table has to be combined with grinding.
- The excavated material will be transported and deposited off-site on a licenced waste heap.

3.5.1.2 Excavation and on-site storage

- This option concerns excavation of contaminated material (soil/sludge/waste) from area Spoorwegstraat and from the wastewater basin.
- The waste will be disposed on the sludge heap to isolate the contaminated material. By making a waste disposal, the contaminated material (soil, sludge, waste) is isolated to (1) inhibit direct contact with this material, (2) reduce leaching and dispersion of the contaminants in the soil, and (3) come to a controllable situation in the future.
- The sludge heap is situated above the groundwater table. The underlying groundwater has been affected by salts such as chlorides and sulphates. Based on the soil characteristics, land use and available information, the OVAM has concluded that there is no severe soil contamination and no remediation measures are necessary for the soil present under the sludge heap.

- There is the legal possibility to install this waste heap on the sludge heap. The installation and closure of the waste heap is mainly based on the presence of heavy metals. The FANC will be involved related to the presence of radioactive material (NORM).
- In frame of the BATNEEC (Best Available Technology Not Entailing Excessive Cost) principle, it is not economically reasonable to first remove the CaF_2 sludge to install an impermeable layer at the bottom of the heap (in accordance with the Flemish legislation for waste disposals[6]). There is no natural mineral barrier at the site, but in a study on the permeability of the CaF_2 sludge it was concluded that the sludge already present on the site will have a similar protection level as a natural barrier of 5 m with permeability 1E-09 m s^{-1}. A drainage layer should be foreseen on top of the existing sludge before new contaminated material is brought on the site to ensure fast decrease of the permeability of the underlying sludge and to limit contact of the interstitial water from the top layer to the environment.
- Based on the fact that:
  (1) the waste disposal will be placed on the previously permitted waste disposal of the CaF_2 sludge heap,
  (2) the CaF_2 sludge heap is located above the groundwater table,
  (3) the influence of the sludge heap on the groundwater quality is limited,
  (4) contaminants do not leach easily from the sludge,
  (5) it is economically not reasonable to first remove the sludge to install an impermeable layer at the bottom and
  (6) because of the limited permeability of the sludge the environmental impact will be limited and therefore ensures sufficient protection,
  it is justified to realise the waste disposal without a HDPE-foil.
- The material will be placed on the site in such a way that a minimum space is used, taking their geotechnical behaviour and stability of the underground into consideration. A stable repository will be ensured. An appropriate drainage system will be installed. At the end of the works, a final layer will be foreseen in accordance to the current legislation. This layer will consist of a mineral water limiting layer of 50 cm and a HDPE-foil, a draining layer and a root layer.
- Afterwards, this waste disposal will be controlled through monitoring.

3.5.1.3 In-situ immobilisation

- Through injection of chemical additives, the leachability of the contaminants can be reduced.
- The limited experience with in-situ immobilisation makes it impossible to ensure the long-term effectiveness.
- Costs are highly dependent on location and contaminants present (~90 euro/ton).
  ➔ Based on the uncertainty related to the effectiveness of the technique, the high amount of heterogeneous material and the presence of radioactive pollution makes this a <u>less favourable technique</u> and it will <u>not be included in the further comparison exercise</u>.

[6] Conform to the current Flemish legislation, there should be a bottom layer consisting of a combination of a HDPE foil of 2.5 mm thick and a mineral layer of 5 m and a permeability of <1E-09 m/s. Instead an artificial geological barrier om minimum 0.5 m can also be installed if it guarantees the same protection level.

3.5.1.4 Isolation using a horizontal top layer

- This option comprises covering the CaF_2 sludge, the wastewater basin and area Spoorwegstraat with a layer to limit the contact with the contaminated material and to limit infiltration of rainwater and the subsequent leaching of the contaminants.
- As there are radionuclides present in the material, the covering layer should be constructed in such a way that Rn emanation and exposure to ionising radiation is minimised.
- The covering layer has to be constructed according to the Flemish legislation consisting of different layers and foils.

3.5.2 Expected results

3.5.2.1 Option 1: Excavation and off-site storage

- All contaminated material will be excavated and deposited on another waste deposit.
- Material that contains contaminant concentrations above risk-based remediation values taking into account radioactivity and future land use (natural reserve) will be removed.
  ➔ Expected result = completely decontaminated area but high use of (limited available) capacity of external waste deposit, resulting in insufficient capacity for future remediation activities.

3.5.2.2 Option 2: Excavation and on-site storage

- Contaminated material from the Spoorwegstraat and the wastewater basin will be excavated until the risk based-remediation values are obtained taking into account radioactivity and future land use (natural reserve).
- The biggest difference with option 1 is that within option 2 the sludge heap (area 1 on Figure 1) will not be excavated but used as waste deposit. By piling up the material, an optimal use of the available space will be guaranteed.
- Afterwards, for the waste deposit, there will be land use limitations to guarantee the top layer is not affected. Due to possible radon exhalation, this zone cannot be used as a residential area. But as this zone is intended to be a natural reserve and is labelled as a radon risk zone, this is unlikely to happen.
  ➔ Expected result = decontamination of area Spoorwegstraat and wastewater basin and isolation of contaminants on the sludge heap (transferred into a waste deposit) with optimal use of the available space.

3.5.2.3 Option 3: Isolation using a horizontal top layer

- By installing a horizontal top layer, contact with the contaminated material is prevented and infiltration of rainwater will be minimal with a possible improvement of the groundwater quality.
- Similar as for option 2, there will be limitations to the future land use to ensure the top layer stays intact. However, in this case, three different areas will be isolated, compared to only one central area in the case of option 2 which is more efficient to control.
  ➔ Expected result = isolation of contaminants of the sludge heap, the wastewater basin and area Spoorwegstraat.

3.5.3 Impact on humans and environment

3.5.3.1 Option 1: Excavation and off-site storage

- Within this option, complete removal of the source is foreseen resulting in maximal improvement of the soil quality.
- The decrease in (valuable) capacity of the external waste deposit is an important disadvantage of this option.
- Excavation of the contaminated material and transportation over public roads will have an environmental impact related to noise, traffic and dust. Material can be sprayed with water to reduce the formation of dust. Impact related to traffic and noise can be minimised through several measures such as choosing the best road, optimally organising the works, consulting different stakeholders, etc. In addition, measures should be taken to minimise exposure to radionuclides.

3.5.3.2 Option 2: Excavation and on-site storage

- Removal of the source at the wastewater basin and the Spoorwegstraat will result in a maximal improvement of the soil quality at these two locations.
- Installation of the waste deposit on the sludge heap will result in a higher relief which can be seen as pollution of the horizon. The waste deposit will finally not be higher than the adjacent hill and another neighbouring waste heap.
- Drainage of the infiltration water and rain water will ensure an improvement of the groundwater quality.
- Excavation of the material and transportation will have a certain impact on the environment such as dust, noise, extra traffic, change in public perception, etc.
- A study has been made by an external consultancy company and different independent experts to map the environmental effects of this remediation strategy and indicate countermeasures to limit the impact. Possible impact on humans, fauna and flora and the landscape based on noise, water emissions, dust, radioactivity, air emissions, transport, etc. were evaluated and countermeasures were suggested based on the relevant legislation and possible techniques (Sertius, 2014).

3.5.3.3 Option 3: Isolation using a horizontal top layer

- Contaminated material is isolated from the environment making it a controllable situation.
- This should lead to an improvement of the groundwater quality.
- The affected area remains the same size.
- When installing the top layer, there can be an environmental impact related to noise and traffic. Finally, there will be a visual impact related to the height of the covered areas.

3.5.4 Future limitations of site use

3.5.4.1 Option 1: Excavation and off-site storage

- There are no limitations for future land use of the site as all the waste is transported to an external waste deposit.

3.5.4.2 Options 2 and 3: Excavation and on-site storage or isolation using a horizontal top layer

- There are limitations for future land use in both cases where the contaminated material was isolated (one location for scenario 2 and three locations for scenario 3) to ensure the cover is not disturbed. Regular controls need to be done related to the effectivity of the isolation, no deep-rooted trees may grow on these sites and there can be no excavation in the future without permission of the authority. It is also prohibited to build buildings on top of this radioactively contaminated material but this is unlikely as the area is considered natural reserve.

Based on the selection procedure discussed in this document, it was decided to excavate the contaminated material at the wastewater basin and the Spoorwegstraat area and store it on the sludge heap making it a controlled waste deposit. The company (responsible for the contamination problem) is responsible for providing all the necessary information needed to evaluate the need for remediation and selecting the best option. This includes financing the supporting studies that need to be done by independent experts to make an informed evaluation of the different criteria in the multi-criteria decision analysis. The company is responsible for the coordination and execution of the remediation works. Based on the information provided by the independent experts and the legislative framework (i.e. Flemish soil decree and implementing order), OVAM decides on the remediation need and evaluates the proposed remediation technique. As OVAM is responsible for the chemical contamination, advise on the radiological part is provided by FANC (e.g. evaluate the radiological impact and safety measures for the workers and the public). OVAM provides the experts with guidelines on how to pre-select relevant techniques and on how to evaluate and compare the different remediation options.

4 Detailed information on remediation costs and calculation of scores

Remediation costs

Option 1 – Excavation and off-site deposition

SANERINGSVARIANT 1: ONTGRAVEN EN OFF-SITE STORTEN						
Uitgangsprincipes:						
* ontgraven 1,5 miljoen m³ (calciumdifluorideslib, stortmaterialen, verontreinigde gronden)						
* storten op slibbekken veldhoven						
* transport via weg						
Post	Beschrijving	Eenheid	EP	VH	TP (excl.BTW)	TP (incl. BTW)
1	Voorbereiding					
	Project voorbereiding en opvolging	GP			350000,00	423500,00
	Plaatsbeschrijving	GP			10000,00	12100,00
	Veiligheidscoördinatie	GP			130000,00	157300,00
2	Civieltechnische werken					
	Waterhuishouding beheer tijdens graafwerken	GP			25000,00	30250,00
	uitgraven slib	ton	2,00	1995000,00	3990000,00	4827900,00
	uitgraven verontreinigde grond	ton	2,00	272000,00	544000,00	658240,00
	inrichten wasplaats op de saneringslocatie	GP			15000,00	18150,00
	slib naar slibbekken Veldhoven	ton	3,50	1995000,00	6982500,00	8448825,00
	verontreinigde grond naar slibbekken Veldhoven	ton	3,50	272000,00	952000,00	1151920,00
	storten slib op slibbekken Veldhoven	m³	5,00	1330000,00	6650000,00	8046500,00
	storten grond op slibbekken Veldhoven	m³	3,00	170000,00	510000,00	617100,00
3	Verminderde milieuheffingen (voor storten)	ton	4,37	2267000,00	9906790,00	11987215,90
4	Milieukundige begeleiding (10%)				2015850,00	2439178,50
5	Onvoorziene kosten (10%)				2015850,00	2439178,50
	TOTAAL VAN DE WERKEN				34096990,00	41257357,90
	VH = vermoedelijke hoeveelheid					
	EP = eenheidsprijs					
	TP = totaal prijs					

Option 2 – Excavation and on-site storage (installation waste deposit)

SANERINGSVARIANT 2 : ONTGRAVEN EN ON-SITE BERGEN						
Uitgangsprincipes:						
* inrichten saringsberging thv slibbekken Kepkensberg (+/- 2 miljoen m³ bergingscapaciteit)						
De afdichtlaag en eindafdek zal als volgt opgebouwd worden:						
* kleimatten						
* HDPE-folie 2,5 mm						
* drainagelaag (onder de vorm van drainagematten met beschermingsgeotextiel)						
* teelaardelaag (dikte 1,5 m)						
Post	Beschrijving	Eenheid	EP	VH	TP (excl.BTW)	TP (incl. BTW)
1	Voorbereidende werken					
1,1	werfinrichting	GP			10000	12100,00
1,2	ontbossing, opbreken omheining, aanleg wegenis, aanleg wielwassing plaatsen nieuwe omheining	GP			100500	121605,00
1,3	herprofilering van de buitendijk slibbekken Kepkensberg	GP			52572	63612,12
1,4	aanleg drainagesleuven en afwateringssysteem, variante uitgraving en bouwafval	GP			70000	84700,00
1,5	Inzaaien voetdijk	GP			14832	17946,72
2	Inrichten, vullen en afwerken cellen 1 t.e.m. 4					
2,1	cel 1					
	inrichten en afwerken	GP			1716060	2076432,842
	vullen compartimenten	m³	7	150000	1050000	1270500
	afgraven V-vormig terrein + AWWB	m³	3,7	150000	555000	671550
2,2	cel 2					
	inrichten en afwerken	GP			1774133	2146700,45
	vullen compartimenten	pm				
2,3	cel 3					
	inrichten en afwerken	GP			1784837	2159653,01
	vullen compartimenten	pm				
2,4	cel 4					
	inrichten en afwerken	GP			2164306	2618809,78
	vullen compartimenten	pm				
4	studies en supervisie, milieukundige begeleiding en nazorg: 5%	GP			464612	562180,50
5	contingencies: 10%	GP			929224	1124360,99
	TOTAAL VAN DE WERKEN*				10686076	12930151,40
	VH = vermoedelijke hoeveelheid					
	EP = eenheidsprijs					
	TP = totaal prijs					
	Om vergelijking met saneringsvariant 1 en 3 mogelijk te maken dient rekening gehouden te worden met de berging van circa 150000 m³ saneringsmateriaal én afdichtlaag + eindafdek voor volledige saneringsberging					

Option 3 – Isolation by installing horizontal top layer

SANERINGSVARIANT 3 : Horizontale bovenafdichting						
Aanleg bovenafdichting thv V-vormig terrein (0,8 ha) + AWW (10 ha) + slibbekken (21 ha)						
Uitgangsprincipes:						
De horizontale bovenafdichting zal als volgt opgebouwd worden:						
* kleimatten						
* HDPE-folie 2,5 mm						
* drainagelaag (onder de vorm van drainagematten met beschermingsgeotextiel)						
* teelaardelaag (dikte 1,5 m)						
Post	Beschrijving	Eenheid	EP	VH	TP (excl.BTW)	TP (incl. BTW)
1	Voorbereiding					
	Project voorbereiding en opvolging	GP			350000,00	423500,00
	Plaatsbeschrijving	GP			12500,00	15125,00
	Veiligheidscoördinatie	GP			100000,00	121000,00
2	Civieltechnische werken					
	Voorbereidende werkzaamheden, werfinrichting	GP			200000,00	242000,00
	stabiliteitsstudie	GP			90000,00	108900,00
	drainage	GP			1600000,00	1936000,00
	egalisatiewerken en grondverzet	GP			1400000,00	1694000,00
3	Horizontale bovenafdichting					
	Aanleg bovenafdichting					
	kleimatten	m²	6,00	318000,00	1908000,00	2308680,00
	HDPE-folie 2,5 mm	m²	10,00	318000,00	3180000,00	3847800,00
	drainagematten met beschermingsgeotextiel	m²	6,00	318000,00	1908000,00	2308680,00
	teelaardelaag (1,5 m dik incl. inzaaien)	m²	10,00	318000,00	3180000,00	3847800,00
4	Milieukundige begeleiding en nazorg (10%)				1392850,00	1685348,50
5	Onvoorziene kosten (10%)				1392850,00	1685348,50
	TOTAAL VAN DE WERKEN				16714200,00	20224182,00
	VH = vermoedelijke hoeveelheid					
	EP = eenheidsprijs					
	TP = totaal prijs					

Calculation of the scores attributed to the remediation costs

The scores that are attributed to the remediation costs are calculated according to the OVAM guidelines (OVAM, 2018).

K1 = Cost option 1 = 41.26 M€

K2 = Cost option 2 = 12.93 M€

K3 = Cost option 3 = 20.22 M€

Kt = K1 + K2 + K3 = 74.41 M€

V = number of options = 3

St = number of scores to be divided = 5 x V = 15

The scores can be calculated as follows:

Score option 1 = St/(V-1) x (Kt-K1)/Kt = 15/(3-1) x (74.41-41.26)/74.41 = 3.5

Score option 2 = St/(V-1) x (Kt-K2)/Kt = 15/(3-1) x (74.41-12.93)/74.41 = 6.0

Score option 3 = St/(V-1) x (Kt-K3)/Kt = 15/(3-1) x (74.41-20.22)/74.41 = 5.5

5 References

Unless specified otherwise, the information used in this document comes from:

OVAM dossier nr. 832 (2015) Derde gefaseerd bodemsaneringsproject Kepkensberg & ‘stortplaats spoorwegstraat’.

Other references:

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