Deliverable 13.2: Mutual Understanding of actors' views about optimisation

Work Package OPTI

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Executive Summary

The EURAD-2 Strategic Study Work Package *"HLW Repository Optimisation Including Closure"* (OPTI) aims to foster a shared understanding and provide recommendations on methodologies and future activities related to optimisation. During two workshops, waste management organisations (WMOs), technical support organisations (TSOs), research entities (REs), civil society organisations (CSOs), regulators, and OPTI stakeholder groups exchanged views on what optimising a disposal programme entails, their respective roles in the process, and how optimisation can be implemented.

All OPTI stakeholders demonstrated a constructive vision and nuanced perspectives on optimisation, reflecting their different roles in the process. They reached consensus that optimisation must take into account prevailing circumstances, including the regulatory framework, the state of knowledge, and the resources available. These circumstances define the space in which optimisation can occur. This space may evolve, for example, following governmental or regulatory decisions, the acquisition of new knowledge, or the accumulation of operational experience. Within this space, optimisation is driven by several interconnected factors: protection, resource efficiency, and decision-making. Optimising one driver may affect another, and changes to one component of a geological disposal facility (GDF) (or even one characteristic of a component) may influence others. These interactions necessitate a holistic approach.

Globally, approaches to optimisation can be grouped into *conceptual* and *applied* categories. Conceptual approaches include impact minimisation, the application of state-of-the-art techniques, flexibility, synergy, modular design, and standardisation. Another conceptual approach involves option-based comparison, focusing on safety attributes such as the performance of structures, systems, and components (SSCs) related to isolation or containment, as well as robustness. Applied approaches include multi-criteria and iterative analyses to optimise design while maintaining compliance with requirements. They may also involve artificial intelligence-based methods, the implementation of a repository management system (RMS), and product breakdown structures that support gradual deployment. In practice, optimisation is achieved by combining conceptual and applied approaches.

According to OPTI stakeholders, optimisation should begin at the earliest stage of a GDF programme. The balance between optimisation drivers evolves throughout the programme's lifecycle. For example, in the initial stages, optimisation is primarily driven by protection and decision-making. Once a site is selected and the initial design defined, resource considerations may become more prominent. Depending on prevailing circumstances and the balance between drivers, the outcome of optimisation will be a solution that is fit-for-purpose—safe, but not necessarily the option yielding the lowest dose, in line with the ALARA principle, which does not seek the absolute minimum dose.

Trust among stakeholders is a critical element of any GDF programme. Engagement with civil society and interactions with citizens are fundamental to achieving socially sustainable solutions. Optimisation that neglects societal concerns risks being perceived as a technocratic exercise rather than a legitimate, inclusive process. While technical and economic optimisation strategies are essential, societal and ethical constraints must also be respected. Any optimisation approach must therefore be embedded within a framework that ensures trust, public participation, risk communication, education, and long-term ethical responsibility.

The mutual understanding achieved within OPTI provides a foundation for future tasks, such as the implementation of a case study on optimisation (OPTI Subtask 3.2) and the identification of key challenges (OPTI Task 4). This common groundwork also paves the way for future joint R&D activities within EURAD-2, particularly regarding the optimisation of SSCs at waste management facilities.

Keywords

Optimisation, High Level Waste repository, Geological Disposal Facility, Decision Making Process

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Glossary

ALARA	As Low As Reasonably Achievable
CS	Civil Society
CSO	Civil Society Organisation
GDF	Geological Disposal Facility
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
MBS	Multi Barrier System
MS	Member State
NEA	Nuclear Energy Agency
OPTI	HLW Repository optimisation including closure
RE	Research Entity
RMS	Requirement Management System
RW	Radioactive Waste
RWM	Radioactive Waste Management
SNF	Spent Nuclear Fuel
SSCs	Systems Structures and Components
SRA	Strategic Research Agenda
TSO	Technical Safety Organisation
TRL	Technology Readiness Level
WMO	Waste Management Organisation

1. Introduction

The strategic study work package OPTI was initiated as part of EURAD-2 to develop a mutual understanding and provide recommendations on methodologies and future activities related to optimisation of SSCs in HLW GDFs. OPTI provides a platform for interactions between members from the three EURAD colleges as well as CSOs, on the optimisation of HLW GDFs. The project team of OPTI includes 23 organisations from 11 European countries. A broad mix of stakeholders is included in the work package: 9 WMOs, 6 TSOs, 9 REs and 1 CSO (Nuclear Transparency Watch, liaising with additional CSOs). Moreover, OPTI is liaising with interested members from the EURAD-2 end-user (including regulators) and stakeholder groups.

The exchanges in OPTI started with a collection of the views of the different OPTI participants. These views about optimisation were presented and discussed in a first workshop held on 23 and 24 January 2025 in Delft, the Netherlands (Figure 1). The exchanges were centred around the "why?", the "how?" and the "when?" there are needs and priorities for optimisation. For instance, views on the possible scope for optimisation at the different phases of a RW disposal programme, the main challenges for optimisation, and the best or existing approaches to optimisation were collected during the workshop. The views of the OPTI participants were refined during a second workshop held on 3 and 4 June 2025 in Prague, the Czech Republic. This paper captures the mutual understanding reached between the OPTI participants**Erreur ! Source du renvoi introuvable.** about optimisation, and summarises the main conclusions of the workshops.

Figure 1 – Participants to the first OPTI workshop, held on 23 and 24 January 2025.

2. Optimisation in the context of GDF

In the Oxford English Dictionary (Oxford University Press, 2025) the term optimisation is defined as *"the action of making the best or most effective use of a situation or resource."* Continuous improvement and optimisation are inherent ambitions of every RWM programme. In EURAD, the roadmap (EURAD, 2021) as well as the SRA (EURAD, 2023) address optimisation. In the EURAD SRA, the *Innovation for Optimisation* is listed as one of the drivers for implementing EURAD activities. Indeed, one strategic goal of EURAD is to support MS in developing and implementing their R&D programs for the safe and long-term management of their radioactive waste, and this implies supporting the MS in their needs for *"… improving robustness, reducing complexity, costs and other resources and optimising RWM routes and advancing technology and solutions"* (EURAD, 2023). In the EURAD roadmap, optimisation is understood as *"… a continuous balancing exercise with requirements and technical solutions to balance the risks among the different barriers. Keeping in mind that there is no such endeavour with zero risk, determine which risks can be (reasonably) taken and which cannot be. Any balancing need to include a cost assessment*." In this regard, the objective of optimisation is the identification the *most suitable* or *optimal* combination of technical provisions of corresponding SSCs.

However, the terminology and understanding about optimisation vary across programmes, countries, and different stakeholders. Within EURAD-2 the exchange about views on optimisation of geological disposal programmes is part of the work package OPTI and the paper in hand. Further, optimisation was addressed by various other institutions and projects such as IAEA, OECD NEA, ICRP, IGD-TP or the SITEX-II project.

In this section, references and definitions of optimisation relevant to RWM are given. These definitions form a common basis for exchanges between the partners of OPTI. An initial differentiation from the wording as used in the WP OPTI is made.

Within OECD NEA, especially the Integration Group for the Safety Case (IGSC) as well as the regulations forum (RF) have addressed optimisation. Several workshops were performed on this topic and documented, see e.g. (NEA, 2010) (NEA, 2008) (NEA, 2014) (Bailey, 2022). Based on the IGSC, the optimisation process is always affected by the possible interactions between the waste characteristics, the site conditions and the design of the GDF. Of course, the waste characteristics will influence the GDF design and maybe the site selection as well. Between site conditions and the design of the GDF, an influence can be identified in both directions. Because of these interactions, the IGSC highlights the importance of a "*total system thinking*" (Bailey, 2022). In OPTI this is described as a holistic approach for optimisation. Furthermore, the IGSC stresses that RWM programmes should follow the principles of transparency, learning processes, forward-looking and respecting the societal constraints.

The IGSC refers in its definitions to the ICRP definition of principle of optimisation. The ICRP (ICRP, 2007) considers the optimisation of the protection as one of the three key principles of the system of radiological protection: the principle of justification, the principle of optimisation of protection and the principle of application of dose limits. The ICRP defines the optimisation of the protection as follows:

(214) "Optimisation is always aimed at achieving the best level of protection under the prevailing circumstances through an ongoing, iterative process that involves: evaluation of the exposure situation, including any potential exposures (the framing of the process); selection of an appropriate value for the constraint or reference level; identification of the possible protection options; selection of the best option under the prevailing circumstances; and implementation of the selected option."

The ICRP thus identifies the protection as the most relevant driver for optimisation. Within a given safety envelope, the optimisation of other drivers can be addressed with respect of the corresponding prevailing circumstances. The term "prevailing circumstances" refers notably to non-technical aspects like cost, social issues, human resources, and national and international political context. The application of the system of radiological protection to the geological disposal of radioactive waste is specifically addressed in the publication 122 of the ICRP (ICRP, 2013). With regard to the application of the optimisation of the protection principle to geological disposal, the ICRP states notably the following:

(80) "The elements guiding or directing the optimisation process should be those that directly or indirectly determine the quality of the components of the facility as built, operated, and closed, where quality refers to the capacity of the components to fulfil the safety functions of containment and isolation in a robust manner. The assessment and judgement of the quality of system components essentially includes the site characteristics, elements of Best Available Technique, as well as the concepts of good practice, sound engineering, and managerial principles. These elements complement and support radiological optimisation when potential impacts in the distant future have to be dealt with."

The ICRP recommendations are taken into account in the development of the IAEA safety standards. For instance, in the Specific Safety Requirements for the disposal of radioactive waste (IAEA, 2011), the IAEA states:

"Optimization under constraints is the central approach adopted to ensure the safety of a waste disposal facility. In this context, the optimization of protection is a judgemental process, social and economic factors being taken into account. The optimization is conducted in a structured but essentially qualitative manner, supported by quantitative analysis."

In IAEA (IAEA, 2020) it is highlighted that the process of optimisation is an iterative process, embedded in the safety assessments. *"The scope and objective for each phase is to develop the design further, to meet regulatory or legal milestones and progressively refine and optimize the design to meet user requirements. The phasing allows review by stakeholders at each major decision point."*

To reach the *best* option, the prevailing circumstances have to be considered, and different options have to be compared based on several criteria, by assessing notably to what extent the SSCs corresponding to the different options will fulfil their safety functions in a robust manner. The concept of robustness is therefore directly linked to optimisation. The IAEA defines robustness as follow (IAEA, 2012):

"A component of the disposal system may be considered robust if it will continue to fulfil its expected safety function(s) no matter what kind of perturbations may reasonably be expected to occur. The disposal system may be considered robust if it continues to provide adequate protection and safety under a wide range of conditions and scenarios that may reasonably be expected to occur."

The radiological protection is not the only driver for the optimisation of a radioactive waste disposal programme. For instance, the overall environmental impact (including for instance the impact of chemotoxic hazards) has to be optimised, as well as the costs of the disposal programme. Drivers for optimisation can be:

- Long-term safety
- Operational safety, including conventional safety
- Radiological protection
- Robustness
- Costs and affordability
- Sustainability
- Environmental impact
- Impact to society
- Local impact to the community

As stated by the NEA (NEA, 2008):

"A distinction needs to be drawn between optimisation of radiological protection, optimisation of overall protection, in the sense of protection of man and environment from all types of hazards, and system optimisation, in the sense of protecting man and the environment from all types of hazards and taking

account social and economic constraints. The national and international guidance seem to be evolving in favour of system optimisation, although this is not always stated clearly."

These definitions and considerations from the ICRP, IAEA and NEA imply that optimisation of a radioactive waste disposal system is a holistic process, covering the entire disposal system and not only its safety and radiological protection aspects. Optimisation is achieved in a stepwise and iterative manner and has to involve all relevant RWM stakeholders. In the work package OPTI, the following stakeholders are involved: WMOs (as implementers), regulators, TSOs, REs, and CSOs. These stakeholders exhibit nuanced views of optimisation, attributable notably to their heterogeneous roles in a RWM programme.

3. Actors' views about optimisation for a GDF

As noted in section 2 (and in the IGD-TP position paper (Gaus, et al., 2023)), optimisation involves both a holistic approach and several RWM stakeholders. In this context, optimisation is a continuously on-going multi-criteria process driven by several drivers. These drivers are in the interest of all stakeholders, but the chosen methods and priority weighting may vary between stakeholders. The following discussion elucidates the roles of the different stakeholders and their nuanced views on optimisation. The section summarises the exchanges within OPTI. As mentioned in the introduction, members of the EURAD-2 OPTI end-user and stakeholder groups (e.g. regulators) contributed to these exchanges. The views from the regulators are considered in section 3.2 about TSOs.

3.1 Waste Management Organisations (WMOs)

In the view of the WMOs, only concepts for disposal of waste that are safe and secure can be implemented. HLW is disposed of in facilities constructed in stable geological formations. Safety, security and safeguard measures will continuously be taken during all stages of the GDF implementation. The implementation covers the initial safety case for licensing, the construction of the GDF, the emplacement of waste and closure of the GDF. The implementation of the disposal of waste always includes the two important safety aspects to maintain a healthy working environment and to prevent hazards to the public.

After closure of the GDF, an MBS of engineered and natural barriers minimizes contaminant releases by which the biosphere could be affected negatively. The set of barriers have at least one safety function. Design requirements that satisfy these safety functions can only be set for engineered barriers, respectively man-made systems. For the natural barriers only target properties can be defined but not influenced. Engineered barriers function in the post-closure phase but can also have functions before the complete closure of the GDF, e.g. if the closure is performed stepwise or in parallel to the disposal. Design requirements can be defined. The design specifications (which materials with which physical and chemical properties, dimensions of these materials such as thickness and diameter, how to manufacture and install them) that satisfy these design requirements will gradually become more detailed upon the progression of implementation of disposal of waste.

Only sites and disposal depths are selected that ensure isolation and confinement until the HLW has decayed to the radiotoxicity of uranium ore. The calculated radiological exposures from the potential radionuclide releases from the MBS are several orders in magnitude smaller than the background radiation. Before a site is selected, the input for these calculations with different types of long-term evolutions of the MBS comes from the design specifications that satisfy the design requirements, expected properties of the host rock and its geological setting.

Design requirements are set with the available system understanding in the pre-closure and post-closure phases and set conservatism. This conservatism ensures radiological exposures as low as reasonably achievable for the workers and the public. To a limited extend the conservatism is linked to uncertainties as well. A reduction of the conservatism is a part of the optimisation task. Optimisation is a key process to improve and adapt the system. The optimisation can be motivated by different drivers. To ensure radiological exposures as low as reasonably achievable was already mentioned. Other drivers can be e.g. an extended level of knowledge and experiences during the operation or the evolution of technologies. In result, specific SSCs could be in focus of an optimisation process. A balance between different drivers is of importance. Safety as a top priority remains but the GDF or its SSCs can be optimised with the costs for the construction and the maintenance of the GDF (lifecycle costs). The lifecycle costs and closure costs of the GDF is preferably determined with the choice in technologies with a TRL of 8/9 (see for instance in the following reference for a definition of the TRLs: (European Commission: Directorate-General for Research and Innovation, 2025)). The uncertainty in these costs is high before a site is selected, if the TRL is low and if there is a lack in scientific and engineering knowledge to clearly define design requirements. This uncertainty in costs gradually reduces upon implementation of disposal of waste and will evolve during the implementation. During the lifetime of the GDF, the TRLs of other technologies will change with time and the availability of materials to manufacture engineered barriers can change. The optimisation of the GDF design provides the flexibility to incorporate emerging, sufficiently tested technologies and engineered barrier materials that meet the required performance criteria. Inclusion of these technologies in the future and replacing materials for engineered barriers can be challenging if the working procedures need to be changed and if people with different qualifications are required for the implementation of these new technologies.

Safety is always provided in the pre-closure phases and the calculated safety provided by the MBS in the post-closure phase is continuously updated with the measured and monitored properties of the host rock and installed engineered barriers. An update or optimisation of the EBS may lead to a reduction in the conservatism. However, less conservative calculations can allow an update or optimisation of the EBS as well. A regular update of the safety case is part of this optimisation process and may set for the definition of the design requirements.

3.2 Technical Safety Organisations (TSOs)

The main roles of the expertise function[1] are to provide regulators with an independent review of safety cases prepared by WMOs, and to help other stakeholders, particularly people from host communities, developing trust in the safety of the RWM. Within the SITEX-II project[2] (Bernier, et al., 2018), several TSOs contributed to a position paper about optimisation in the context of radioactive waste disposal. Considering this input and the exchanges during the OPTI workshops, the TSOs involved in OPTI have developed the following mutual understanding of their roles and needs in the optimisation of radioactive waste disposal programmes.

It is recognised that different drivers for optimisation exist, which will influence the siting, the design, the construction, the operation and the closure of a GDF. These drivers can be related to safety and security (e.g. optimisation of nuclear safety and radiation protection, security, conventional safety), but also to techno-economical aspects (e.g. drivers such as optimisation of costs, feasibility, resources and material availability, durability and even optimisation of the decision-making process itself). The safety regulatory body defines expectations related to the optimisation of nuclear safety and radiation protection (in short: 'safety optimisation'), and some TSO's even play a role in assisting regulatory bodies in the development of regulation that document these requirements. The focus of TSO's is therefore on safety optimisation. The role of the TSO is to verify whether the expectations from the regulatory body related to safety optimisation have been properly met. TSO's are aware of the other drivers for optimisation, such as optimisation of costs and resources. For example, optimisation of costs plays a role in assuring sufficient funding remains available to implement the disposal facility. Safety is however always the constraint for these other drivers for optimisation.

TSOs consider that the optimisation approach should not be restricted to individual aspects of, for example, the safety concept, but should be holistic (i.e. address the optimisation of the global system, considering the interactions between SSCs contributing for instance to the long-term safety, the

[1] SITEX defines the expertise function as the function providing support to the regulatory function fulfilled by safety authorities. Depending on the national context, the expertise function can be fulfilled by organisations external to the safety authority (for instance a separate TSO) or be internal to the safety authority. For practical reasons, in this document, the acronym TSOs is used to refer to any organisation fulfilling an expertise function as described by SITEX.

[2] SITEX-II is a former EU project which prepared the foundation of the SITEX.Network association, coordinating the TSO College in EURAD-2.

operational safety and the conventional safety). The optimisation process is conducted in an iterative manner by the WMO within the limits of the prevailing circumstances. The optimised safety concept is the safest option constrained by the prevailing circumstances. These circumstances evolve with time, and an option that is considered as optimal at a time could thus become not optimal later because of a change in the constrains. It is recognised that each of the drivers for GDF optimisation has its own prevailing circumstances. Optimisation of costs for example is constrained by material availability, industrial regulations... Moreover, each driver somehow constrains the other driver: safety optimisation will be constrained by costs, and optimisation of costs will be constrained by safety.

The process of safety optimisation should start at the very beginning of the development of the disposal facility. In the early stages, important efforts are put in developing a safety concept that is safe and also optimised from a safety point of view. During the safety optimisation process, iterations of performance and impact assessment can be used as tools to compare options. Feasibility is recognised as an important constraint in the optimisation. Later on in the process, emphasis is put more on optimising costs, feasibility of the construction and operations, material use, … During the optimisation process, TSO's see it as important to remain flexible and develop and maintain knowledge on among others the state of the art, the lessons learned, the challenges, the risks. At the end of the process, the final design and operational organisation will reflect the results of an optimisation process related to all drivers for optimisation, including safety.

Finally, concerning their involvement in the safety optimisation process, TSOs consider that, together with the regulators, they should not intervene in the implementation of the process (e.g. impose options), but they should agree on the optimisation approach and criteria which will be adopted by the WMO. They should also evaluate the application of the approach and the optimised option selected by the WMO. At the end of the process, unreasonable resources may be needed by the WMO to compare a marginal gain in safety between different options. If it is the case, the WMO should select and motivate a choice of option, and the TSO and the regulator will agree or disagree with this choice.

3.3 Research Entities (REs)

The primary role of REs is to provide a scientific, evidence-based, foundation for optimisation and decision-making. The work of REs underpins the continuous improvement of disposal concepts as REs advance knowledge, develop innovative solutions and support their practical implementation, and foster interdisciplinary collaboration between different fields. Thereby, REs cooperate with, support and advise other stakeholders in the optimisation process.

REs contribute to the optimisation process in several complementary ways. They develop approaches that enable the systematic comparison of options at different scales and help define which options should be evaluated further. For instance, REs are developing increasingly sophisticated multi-physics codes to simulate the evolution of the near field and the transport of radionuclides. These numerical tools enable comprehensive sensitivity analyses of critical design aspects, including mechanical requirements, gas generation and migration, near-field temperature evolution, and radionuclide transport (dose). These developments contribute to an improved understanding of the complex couplings between (bio-)chemical and physical processes that govern near- and far-field evolution as well as radionuclide transport. This enhanced understanding supports increased confidence in repository safety and broadens the scope for system optimisation.

By advancing new concepts and techniques, REs expand the space of possible solutions, sometimes even exploring approaches that lie outside prevailing legislative or practical constraints (e.g., alternative disposal concepts, new materials), which may later become viable options. REs also play a strategic role in guiding research priorities across the different stages of a disposal programme: from early geological investigations to later engineering, automation, or monitoring solutions. This adaptability requires not only flexibility in R&D focus but also effective knowledge transfer and training as new disciplines and organisations enter the field.

As national disposal programmes progress from conceptual development to site selection, design and construction, the focus of REs is expected to shift from generic and fundamental research to applied research, site-specific studies, design considerations, and the development of engineering solutions. At the same time, maintaining a strong foundation in fundamental science remains essential to preserve flexibility in optimisation efforts and ensure preparedness for emerging challenges and novel technologies, among others.

By carrying out independent, responsible research in accordance with the guiding principles of scientific integrity, REs contribute to preserving objectivity, transparency, and public trust. At the same time, REs work in close cooperation with WMOs, TSOs, and CSOs, ensuring that scientific advances are translated into practical solutions, regulatory frameworks, and participatory processes that support optimisation. Emerging tools such as digital twins, artificial intelligence and advanced visualisation further enhance shared understanding and support evidence-based decision-making. Such contributions are indispensable for WMOs, TSOs and CSOs, helping them to translate scientific advances into regulatory frameworks and operational practice, while also reinforcing trust among regulators, policymakers, and the public.

In addition to their research function, REs are key institutions for education, training and knowledge transfer, thereby contributing to capacity building and dissemination of knowledge. REs ensure that both current and future generations of professionals are equipped with the necessary skills to support the safe and effective implementation of geological disposal solutions. This role extends to public engagement, facilitating transparent communication of scientific findings to stakeholders, policymakers, and the broader community.

3.4 Civil Society Organisations (CSOs)

CSOs act as independent observers of RWM projects, monitoring their overall implementation and optimisation. As "watchdogs", distinct from both implementers and regulators, they raise concerns, support improvements to institutional frameworks, and protect the interests of society at large, from local communities to European stakeholders. CS recognises optimisation as a necessary component of complex industrial projects involving multiple, sometimes conflicting interests. Its role is to ensure that key concerns, especially those related to safety, costs and trust, are openly discussed and addressed transparently, with CS participation in related decisions.

From the CS perspective, safety is consistently identified as the foremost priority and the foundation of public trust. In any assessment of trade-offs, safety should remain the primary criterion guiding decisions, as it is regarded as a fundamental condition for establishing and sustaining public trust. However, it may require navigating complex compromises, such as those between short-term operational safety (e.g. reducing worker exposure, promoting automation) and long-term safety objectives (e.g. limiting future generations' exposure, costs and burden), or between long-term safety and reversibility or retrievability considerations. Thus, optimisation strategies perceived as prioritising cost-effectiveness or project feasibility over safety may pose risks to public trust: ensuring that safety remains central is critical for maintaining trust and legitimacy.

CS engagement with technical optimisation focuses on its societal implications (safety, security, costs and trust, etc.). Its contribution is to bring qualitative insights on how optimisation criteria and boundaries are defined and interpreted (e.g. the "prevailing circumstances"), explore the regulatory aspects of technical issues, and to promote continuous dialogue with technical experts.

Transparent and professional risk communication is crucial to trust. Effective knowledge management and public education are essential to sustain informed dialogue and engagement. Developing inclusive communication strategies and awareness programmes, providing accessible, reliable information and maintaining open dialogue strengthen public confidence, understanding, trust, and long-term participation in RWM governance, whereas opacity undermines it.

Democratic frameworks, clear legal bases, education, and adequate resources are essential for meaningful CS participation. Transparency and inclusiveness must be embedded throughout the governance of RWM projects. These requirements, aligned with the Aarhus Convention (UN, 1998), should be addressed throughout the entire lifecycle of any project. The concept of long-term stewardship offers a valuable framework for guiding both the optimisation process and the overall governance of RWM programmes.

CS interest in optimisation extends beyond its technical dimensions and is closely tied to long-term societal and financial considerations, particularly the interplay between cost and safety across generations, from pre-siting to post-closure phases. Optimisation must balance cost-efficiency with safety as the overriding objective. While cost considerations should not override safety imperatives, they remain a legitimate concern that cannot be entirely overlooked. Public funds should be used transparently and responsibly to ensure sustained safety across generations: public authorities may need to establish long-term financial mechanisms to guarantee the continuity of safety measures across generations.

There is a societal demand that optimisation should integrate governance, transparency, participation, and ethical reflection. The decision-making process itself must be continuously improved to address the adequacy of the legal framework, the transparency of procedures, the establishment of additional educational approaches and the effective inclusion of the public in deliberative processes. Thus, it should be required to take into account the overall governance of the programme, as well as the full range of radioactive waste management steps and their interdependencies, including pre-disposal activities, the siting process and site selection, the integration of best available technologies (including those that may emerge during the implementation phase), and the potential interactions between retrievability provisions and long-term safety. In this regard, retrievability can be seen as a potential lever for enhancing the optimisation of the programme's overall governance.

The optimisation of governance must address intergenerational responsibilities, ensuring that neither current nor future generations bear disproportionate risks. Knowledge transmission and rolling stewardship are key to maintaining safety and trust over time.

In summary, CS views optimisation as a holistic process integrating technical, governance, and societal dimensions, where long-term safety, transparency, and ethics are central.

4. Consensus view

As illustrated in the previous subsections, the OPTI stakeholders (WMOs, TSOs, REs, and CSOs) have a constructive vision and nuanced views on the approach to optimisation, as it relates to their different roles in the optimisation process. The following consensus view can be found between these different stakeholders.

The optimisation process must take into account the prevailing circumstances, including the regulatory framework, the state of knowledge and the available resources. As illustrated in Figure 2 and further detailed in section 6, these prevailing circumstances constrain the space in which the optimisation process can be conducted. The prevailing circumstances, and thus the space for optimisation, may evolve for instance following governmental or regulatory decisions, the acquisition of new knowledge and the accumulation of experience.

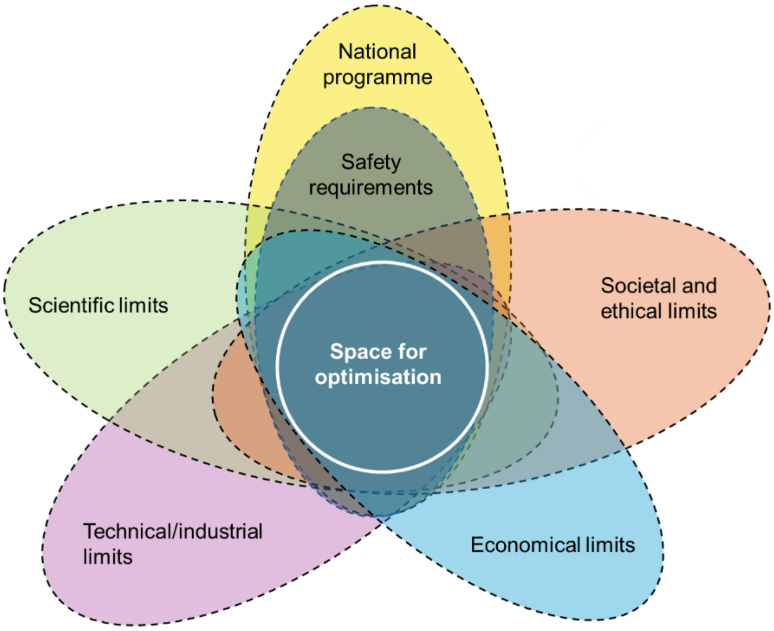

Figure 2 – Several prevailing circumstances constrain the space for conducting the optimization. Note that the figure is not at scale, it is for illustration only.

In the space for optimisation, the optimisation process is driven by several drivers, which can be categorised as follows: drivers related to optimising protection, resources and the decision-making process. As shown in Figure 3, these drivers are interconnected, meaning that optimisation according to one driver may affect optimisation according to another. Furthermore, optimising one component of a GDF (or even one characteristic of a component) may affect others. These interactions require a holistic approach to optimisation, in which the potential impact of optimisation options on the entire GDF is compared iteratively based on multi-criteria analyses.

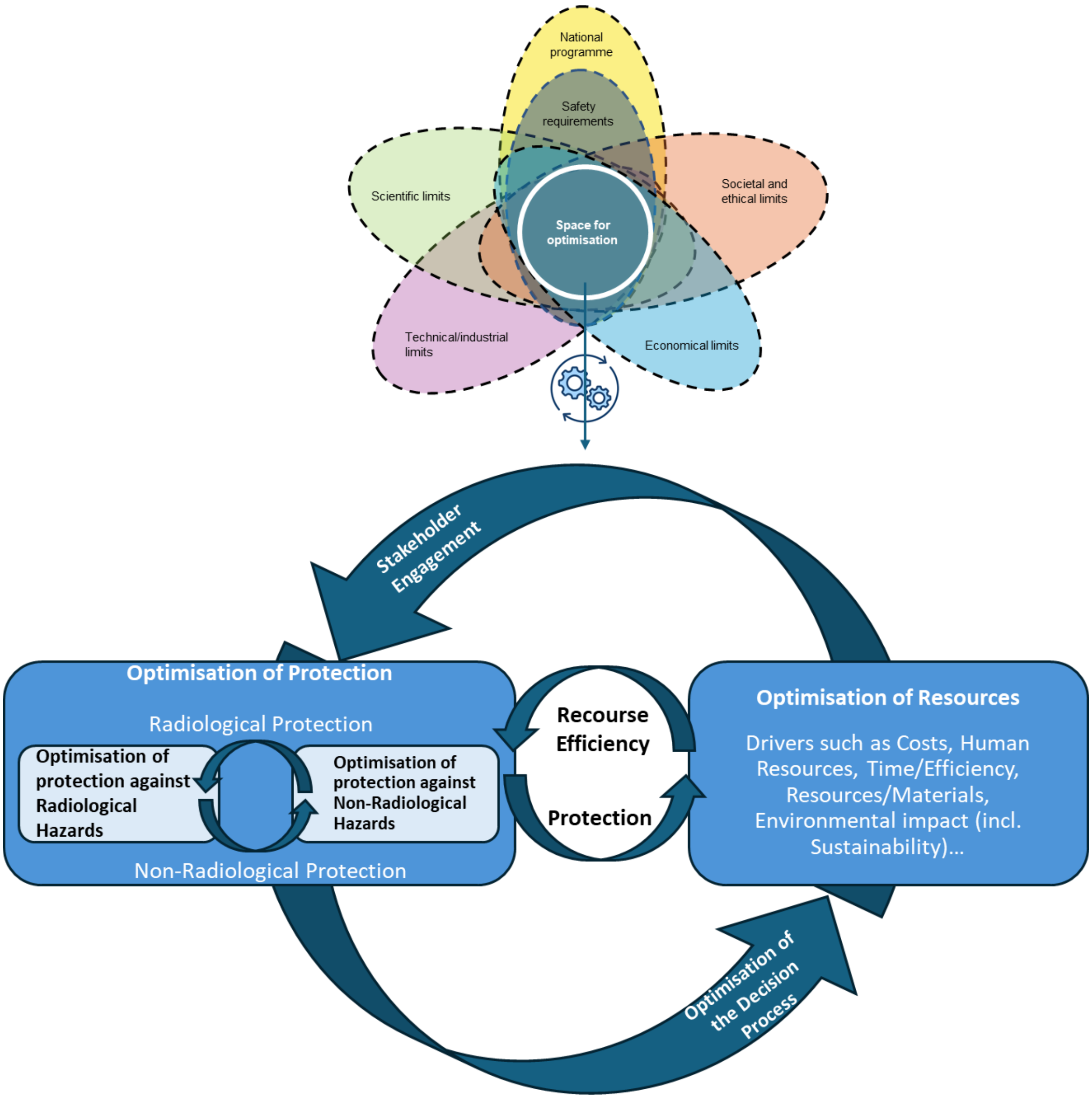

Figure 3 – Optimisation process and its drivers, within the optimisation space.

The optimisation process should begin at the early stage of a GDF programme. However, the balance between the various optimisation drivers will evolve throughout the programme's lifecycle. For example, at the start of a disposal programme, the optimisation process is primarily driven by protection and decision making. Once a site has been selected and the initial design defined, the optimisation process could become more resource driven. Depending on the prevailing circumstances and the balance between the drivers, the outcome of the optimisation process will achieve a solution which is fit-for-purpose (meaning that it will be safe but may not necessarily be the option that results in the lowest dose, in the same way that the ALARA principle does not seek the absolute lowest dose). A further explanation about the approaches to optimisation is provided in section 5. 2Implementing the optimisation process involves several stakeholders (including Civil Society). The key roles of these stakeholders in the optimisation process are:

- TSOs/regulators: define expectations and requirements with regard to the protection, validate the optimisation process proposed by the WMO and the options affecting the protection selected by the WMO throughout the implementation of this process.
- WMOs: propose and implement an optimisation process that meets the expectations and requirements of the regulator/TSO. In this framework, at the different steps of the process, they evaluate and select different options for optimisation.

- REs: support the implementation of the optimisation process by advancing the science, contributing to the development of innovative solutions, and fostering interdisciplinary collaborations. Contribute to capacity building and dissemination of knowledge through education, training and knowledge transfer.
- CSOs: monitor the optimal implementation of the decision-making process related to disposal programmes, independently from the missions of the regulators, TSOs, WMOs and REs.

5. Approaches to optimisation

As mentioned in the consensus view presented in section 44, the balance between the different drivers for optimisation will evolve over the lifecycle of a disposal programme. The obtention of a license for the construction of a GDF on a chosen site can mark a significant milestone in the optimisation process. In such advanced stages of implementing geological disposal facilities, optimisation efforts are closely tied to the detailed design phase. At this point, economic considerations play a more important role in guiding optimisation strategies. Safety is ensured and reviewed through regular updates to the safety case, and key decisions regarding the overall concept have already been finalised. Cost-effective solutions can be pursued without compromising safety—for instance, by utilizing existing infrastructure for surface facility construction, which also helps minimize environmental impact. Further optimisation may include refining the repository layout, enhancing the design and manufacturing of engineered barrier systems, and streamlining waste delivery logistics and supply chains.

During the different programme stages, an evolution of the balance between the drivers for optimisation might affect the specific tools used for conducting the optimisation process. A number of common expectations are identified regardless the stage of the programme:

- Optimisation starts at the beginning of the programme and is a continuous process through all phases, including the definition of the inventory for the GDF and the classification system of the waste.
- The optimisation process should be traceable. A Change Management System is needed to implement new chosen options.
- Optimisation should be carried out in a holistic way. A holistic understanding of the system is indeed needed to compare options, and a common framework is necessary to evaluate how the system is impacted by alternative options or changes.
- Optimisation is a multi-criteria, iterative process that should be performed while maintaining adherence to safety and design requirements.
- The optimisation process should be science-based. Data collection is therefore important. Large-scale tests in underground research laboratories and simulations should be used to support optimisation.
- Optimisation should consider new developments in science and engineering.
- The optimisation process should consider uncertainty assessment and management. This relates to the concept of robustness, introduced in section 2.
- Digital and collaborative tools can support optimisation process and the communication between stakeholders; a systematic approach is beneficial to ensure that findings are preserved over long timescales.
- Optimisation should not rely solely on isolated expertise. Instead, it should draw upon collective intelligence, meaning the shared knowledge, experience, and innovation from a wide range of contributors or stakeholders. This should include insights from other industrial areas, such as construction, logistics, manufacturing, and digital technologies.
- Optimisation should account for the different perspectives of the various stakeholders.
- Periodical safety reviews should be used to assess optimisation throughout the programme life.

2Beside these common expectations, the exchanges at the OPTI workshops highlighted some specific approaches which could contribute to the optimisation process. It was noted that these specific approaches varied from a programme to another and from a type of RWM stakeholder to another. It was also noted that the strategy for optimisation is still under development in some programmes at an early stage. These specific approaches could be grouped into more "conceptual" or "applied" approaches. Conceptual approaches are for instance impact minimisation, application of state-of-the-art techniques, drawing upon flexibility, synergy, modular design, and standardisation. Another approach follows an option-based comparison, based on safety attributes such as performances of SSCs related to isolation or containment, as well as robustness.

Applied approaches include the use of multi-criteria and iterative analysis to optimise design while maintaining adherence to design requirements. Applied approaches may include the implementation of a RMS, a product breakdown structure, favourable for a gradual deployment, and artificial intelligence-based methods. They aim at supporting the optimisation of the system as a whole, but also of its different subsystems. In practice, the optimisation process is conducting by combining conceptual and applied approaches. The process will include periodical Safety Case updates and reviews.

An RMS is a versatile and systematic approach which can support the effort and assist users in (i) orientation and organisation of data, and (ii) selecting the best approaches, methods, and tools for developing and implementing a disposal facility. The RMS will grow in its level of detail over time. In early stages, the RMS-based optimisation is driven by an assessment of main directions of the programme. Early concerns include the comparison of strategic choices, concepts, and considerations balancing safety, cost, stakeholder views and other factors. Within EURAD, guidance about RMS development and use in the framework of GDF was already issued (EURAD, 2024) (Zuidema, 2024). As a GDF programme advances, the optimisation process becomes more quantitative. Typical decision-making methods and assessment methods can be applied, such as e.g., multi-criteria analysis. Prediction of the system evolution and the associated modelling become more important as well.

The aforementioned findings of the OPTI workshop are globally well aligned with the position paper written by several TSOs within the SITEX-II project (Bernier, et al., 2018), the 2022 IGD-TP position paper (Gaus, et al., 2023) and symposium on the role of optimisation in radioactive waste geological disposal programme. More specifically, they are consistent with the following R&D directions identified in the position paper to support approaches to optimisation: exploration and testing of novel materials and technologies, digital environments and evaluation tools to support optimisation, as well as learning from other industries.

6. Limits to optimisation

While optimisation is a key objective in a GDF programme, it is inherently constrained by several factors. As mentioned in section 2, regulatory frameworks often refer to "prevailing circumstances" as a guiding principle, acknowledging that repository design and management must be responsive to practical constrains and non-technical aspects. These prevailing circumstances shape the extent to which optimisation is feasible and achievable (see in Figure 2). They include scientific, industrial, economical, societal and ethical limits.

First, the optimisation of a GDF should rely on the available scientific and technical knowledge. While research can reduce remaining uncertainties[3], it is unlikely that full predictive capacity can ever be achieved. New uncertainties may emerge as programmes progress, requiring continuous reassessment and adaptation of GDF designs.

Technological advancements play a critical role in improving repository designs, but industrial feasibility imposes clear boundaries on what can be optimised. The construction and operation of a GDF must adhere to the regulatory framework as a top requirement (which imposes strict safety standards), as well as standards and recommendations for underground works and other relevant fields. As a

[3] Reducing uncertainty is not the only way to manage uncertainties. For instance, uncertainties could be avoided by a design change. See (Hicks, Crawford, & Doudou, 2023).

consequence, certain design choices may be dictated by practical feasibility rather than theoretical optimality.

Economic feasibility is a crucial consideration in the optimisation of GDF. The development, implementation, and long-term operation of a GDF require substantial financial resources, and cost considerations inevitably place limits on the extent of optimisation. Cost-benefit analyses must guide decision-making, ensuring that safety and robustness are prioritised without imposing excessive financial strain. Understanding cost optimisation in RWM should include an assessment of how financial strategies impact safety, governance, and intergenerational equity. There is a need to optimise financial systems in a way that ensures long-term safety rather than short-term cost savings.

Finally, societal, political and ethical aspects are another important challenge to ensure the maintenance of public trust. If the public perceives that optimisation efforts prioritise cost reduction or efficiency over safety for instance, this can severely undermine trust in both institutions and the RWM process. Safety, regarding both the operational and the long-term scales, is crucial for trust, which itself is both the result and the prerequisite for a good dialogue with CS.

Many elements can enhance or threaten the building of trust among parties, notably the engagement of CS and the interactions with citizens. Effective engagement is not merely a procedural step; rather, it is fundamental to achieving socially sustainable solutions. Optimisation that fails to account for societal concerns risks being perceived as a technocratic exercise rather than a legitimate, inclusive process. Whilst technical and economic optimisation strategies are of paramount importance, it is imperative to acknowledge the fundamental societal and ethical constraints that cannot be neglected in the process. It is essential that any optimisation approach is developed within a framework that ensures trust, public participation, risk communication and education and long-term ethical responsibility.

This long-term ethical framework can also be seen as a limit to current optimisation. However, envisaging the process through concepts such as the rolling stewardship, which involves maintaining and transmitting knowledge over generations, can help navigate through the short-term optimisation needs and the ethical considerations on the long-term.

Finally, it should be noted that, as discussed in sections 44 and 55, the above-mentioned limits to optimisation are expected to evolve over time as national programmes advance from initiation to site selection, site characterisation, construction, and operation and closure.

7. Conclusions and outlook

Within EURAD-2, optimisation is addressed accross many WPs and is recognised as a holistic process within RWM. In this context, the Strategic Study Work Package "HLW Repository optimisation including closure" (OPTI) aims to develop a mutual understanding and provide recommendations on methodologies and future activities related to optimisation. The different WMOs, TSOs, REs, CSOs and regulators involved in OPTI, along with the OPTI end-user and stakeholder groups, exchanged views on what optimisation of a disposal programme entails, their roles in such a process, and how optimisation can be implemented. The views of these stakeholders on optimisation were nuanced, due to their different roles in a disposal programme.

Globally, the approaches to optimisation could be grouped into "conceptual" and "applied" approaches. Conceptual approaches include impact minimisation, application of state-of-the-art techniques, drawing upon flexibility, synergy, modular design, and standardisation. Another approach follows an option-based comparison, based on safety attributes such as performances of SSCs related to isolation or containment, as well as robustness. Applied approaches include the use of multi-criteria and iterative analysis to optimise design while maintaining adherence to design requirements. Applied approaches may include artificial intelligence-based methods, the implementation of a RMS, and a product breakdown structure favourable for a gradual deployment. These approaches aim at supporting the optimisation of the system as a whole, but also its different subsystems. In practice, the optimisation process is conducted by combining conceptual and applied approaches.

According to the OPTI stakeholders, the optimisation process should begin at the early stage of a GDF programme. The balance between the various optimisation drivers will evolve throughout the programme's lifecycle. For example, at the start of a disposal programme, the optimisation process is primarily driven by protection and decision making. Once a site has been selected and the initial design defined, the optimisation process could become more resource driven. Depending on the prevailing circumstances and the balance between the drivers, the outcome of the optimisation process will achieve a solution which is fit-for-purpose (meaning that it will be safe but may not necessarily be the option that results in the lowest dose, in the same way that the ALARA principle does not seek the absolute lowest dose).

Many elements can affect the building of trust among all stakeholders of a GDF programme, notably the engagement of CS and the interactions with citizens. Effective engagement with CS is not merely a procedural step; rather, it is fundamental to achieving socially sustainable solutions. Optimisation that fails to account for societal concerns risks being perceived as a technocratic exercise rather than a legitimate, inclusive process. Whilst technical and economic optimisation strategies are of paramount importance, it is imperative to acknowledge the fundamental societal and ethical constraints that cannot be neglected in the process. It is essential that any optimisation approach is developed within a framework that ensures trust, public participation, risk communication and education and long-term ethical responsibility.

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