The Role of Optimisation in Geological Disposal Programmes for Radioactive Waste

Based on the IGD-TP Optimisation Symposium in Zürich, September 2022[1]

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Abstract

Geological disposal projects are multi-decade endeavours representing considerable budgets. To ensure their success, continuous optimisation of the project is required. The term optimisation in the context of implementing geological disposal facilities has widened from focussing initially on post-closure nuclear safety to many other aspects (e.g., design, engineering, cost, environment and sustainability, acceptance). Optimisation to implement geological disposal has thus become a multi-stakeholder and multi-objective challenge. There is a consensus that optimisation thinking should take place from the start of the programme as key decisions must be made at this stage. Making the trade-offs visible at each decision point or milestone and providing full transparency are needed to avoid undesirable impacts on operational and post-closure safety especially. To support the optimisation efforts of the waste management organisations in various stages of development, the following research and development (R&D) directions have been identified:

Exploration and testing of novel materials and technologies - This entails identification of the potential for further refinement of safety-relevant analysis, reduction of over-conservatism and replacement of existing materials and technologies with higher-, or equally- performing ones. In this context, safety, cost and environmental impact are not automatically competing interests.

Digital environments and evaluation tools to support optimisation - Especially for programmes in the earlier stages, the ongoing digital transition offers major opportunities. The possibility to generate virtual adaptations to the reference concept or to the design of the geological disposal facility and rapidly evaluate these in terms of safety, practicality and (although less easy) acceptance will be a major step forward.

Learning from other industries with respect to optimisation - Optimisation, especially when going hand-in-hand with digitalisation, is taking place in many domains of society, and initiatives that cut across geological disposal and other uses of the subsurface or across the wider nuclear domain can bring major benefit.

Experience from the pioneers in the implementation of geological disposal (Finland, Sweden, France) has made it clear that optimisation towards the operating phase requires continuous efforts and many lessons remain to be learned. Integration of lessons-learned from others and integration of ongoing R&D is needed to avoid duplication. This will support the optimisation efforts of all the waste management organisations involved and thus the progress in implementing geological disposal globally.

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[1] Programme and presentations available on https://igdtp.eu/event/igd-tp-symposium/
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1. Background and evolution of the meaning of optimisation

Geological disposal is the preferred option for the disposal of high-level radioactive waste. After several decades of research and development, the first geological disposal facility is planned to go into operation in Olkiluoto, Finland by the year 2025. Sweden and France are close to constructing a facility and Switzerland has proposed the site for a future geological disposal facility. An overview of the current status, the vision and the strategic research agenda of the main European implementers can be found from the Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP)[6]. The key pillars of the 2040 Vision "Towards industrialisation of radioactive waste disposal in Europe" is shown in Figure 1.

2040 – Towards industrialisation of radioactive waste disposal in Europe		
Safely operate	Optimise & industrialise	Tailor solutions
the first geological disposal facilities in Europe	planning, construction and disposal operations	for disposal of the diverse waste inventories in Europe

Figure 1: The "three pillars" to support the IGD-TP VISION 2040: Safely Operate, Optimise and Industrialise, and Tailor Solutions. These are intended to specifically support the research of the implementers in the various stages of the geological disposal facility programmes.

Given the unique nature of geological disposal facilities and the need to ensure safety over geological timeframes, the post-closure safety has been the focus for decades when developing geological disposal programmes. This is still the case for programmes that are at an early stage, e.g., site selection. Advanced programmes, have, as part of a graded approach, reviewed post-closure safety at several milestones and demonstrated that their mature concepts are safe with large safety margins in place. The post-closure (and operational) safety and performance analyses are strongly steered by ICRP[7] and IAEA[8] guidelines, which have been incorporated into national laws and regulations. While the meaning of optimisation for geological disposal facilities has somewhat shifted with time, the term optimisation was initially reserved or restricted to the optimisation of radiological protection and later also extended to safety.

The concept of geological disposal has significantly matured, especially over the last decade. In many programmes, the initially foreseen, rather schematic, multi-barrier concepts have been replaced by conceptual designs and subsequently, in the most advanced programmes, by detailed designs and operation schemes. This stepwise substantiation of geological disposal facilities accentuated the sheer size of the projects and the complexities that these large infrastructure projects involve in terms of planning, licensing, material and technology selection and production, financing, environmental impact, etc. In fact, geological disposal facilities, with estimated budgets easily exceeding 10 billion Euros, are among a handful of major infrastructure projects that each country must deal with at any given moment in time. Other examples are large tunnelling or public infrastructure projects (e.g., airports). In the context of these large infrastructure projects, optimisation has a much wider definition and describes the process required to improve the performance of the project in terms of safety and implementation and thus also in terms of cost and schedule. In addition, the impact of the project on the environment, not only the local environment but also in the

[6] https://igdtp.eu/document/2020_igd-tp_strategic-research-agenda/
[7] International Commission on Radiological Protection, https://www.icrp.org/
[8] International Atomic Energy Agency, https://www.iaea.org/

context of reducing carbon emissions, has become increasingly important. Thus, minimising the environmental impact has become a further optimisation target. An additional aspect that is not easy to capture, is how to achieve the necessary acceptance among the population and the public. This is important to the implementation part of the project and requires creating a culture of trust that geological disposal is the safest solution for the disposal of radioactive waste. The successful operation of multiple geological repositories around the world would significantly contribute to building stakeholder trust and acceptance.

Optimisation to implement geological disposal has thus become a multi-stakeholder and multi-objective challenge in which radiological protection and operational and post-closure nuclear safety take a central role. In order to achieve optimisation, the key choices to make within the existing constraints must be described such that the decision-making can occur in an open and transparent manner. The complexity of the disposal projects and the long timescales involved make defining optimisation steps and choices difficult. Optimisation can involve the entire programme, focus on parts of the programme (e.g. site selection), focus on the design cycle or on the selection of certain materials and technologies, etc. Optimisation strategies must be tailored to the needs of each individual geological disposal programme.

To support this and to highlight the importance of optimisation as a key part of repository realisation and as a driver for Research, Development & Demonstration (RD&D) activities, the IGD-TP organised the Optimisation Symposium in September 2022. The main outcomes of the symposium are interpreted in this paper. The following sections highlight several aspects of optimisation as well as some methodologies to conduct a successful optimisation process.

2. Role of optimisation in a geological disposal programme

Implementing geological disposal is achieved through a succession of development stages (Figure 2). These stages are broadly consistent across national repository development programmes, even if the terminology used can differ. Within this staged process towards radioactive waste disposal, the national programmes of the individual European countries have currently advanced to very different stages (Figure 3). As a result, the role of optimisation in implementing geological disposal is strongly linked to the progress of the programme.

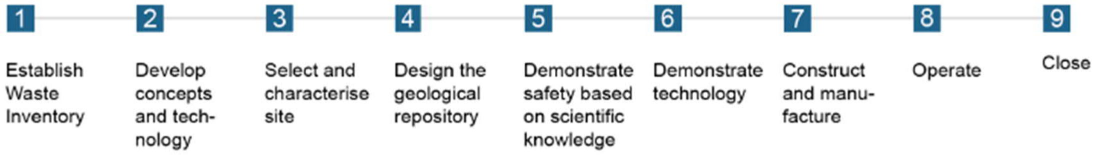

Figure 2: Simplified representation of the main stages in the implementation of geological disposal (Note, in practice these stages will overlap and partial construction and operation licences might be required based on the respective national legislation) (IGD-TP, 2020).

For countries in an advanced stage of implementation, such as Finland, Sweden and France, optimisation is currently linked to the detailed design of a geological disposal facility. In this advanced stage of development, optimisation is strongly economically driven. Safety is demonstrated by regular updates of the safety case, and major decisions related to the fundamental concept have already been made. Economical optimisation can be achieved without compromising overall safety, for example, by taking advantage of existing infrastructure when constructing the surface facilities, which can also reduce the environmental impact. Optimisation can also involve the repository layout, the fine-tuning of the engineered barrier system and its production process, the logistics of waste delivery and supply chain.

The optimisation efforts might result in proposed changes or important updates with respect to the (submitted or granted) license applications for these advanced programmes. Such changes will also continue to occur in the future when these programmes approach the operational phase, and even during operations. A well-established process of interactions between the regulator and the implementer to accommodate these optimisation measures is needed to deliver a state-of-the-art disposal project.

The most advanced programmes were also the first to be confronted with the interface between operational safety and post-closure safety and the need to optimise both. Operational safety measures should not interfere with post-closure safety, but it is recognised that, in practice, operational safety bears the higher risk as the safety margin for the post-closure phase is very high.

The staged implementation, as construction and operation stretch over multiple decades, is a major opportunity for project optimisation. In Finland, the excavation and the on-site construction of ONKALO provided input for several optimisation proposals that have been included in the construction licence. The pilot phase for high-level radioactive waste (HLW) and low-level radioactive waste (ILW) disposal that is part of the French disposal programme will deliver input for future optimisation, especially with regard to the final HLW repository sections that will not be constructed for several decades to come.

Countries such as Switzerland, Belgium and the United Kingdom that are further away from the construction licence application tend to optimise safety and implementation jointly. Indeed, the largest optimisation potential involves the conceptual design stage where key choices must be made within certain constraints. In Belgium for instance, the return of experience gained by the more advanced programmes on how operational safety aspects can impact the layout and design of a geological disposal facility has been used to perform a multi-criteria analysis of different layouts and its integration in operational safety issues together with other potential stakeholder requirements. Switzerland, which plans to submit the general licence application for a combined repository in the Opalinus Clay in 2024, has initiated a major optimisation effort to optimise safety, costs and acceptance before embarking on the construction of the on-site facility for investigations in the early 2030s. Thermal optimisation for the repository design configuration will be one of the key aspects, and RD&D in anticipation of this has already started.

For smaller programmes that are in the generic planning phase, collaboration with different countries can provide large optimisation opportunities. In this case, multi-national shared repositories are the ultimate optimisation opportunity with regard to both costs and safety. The example of the Netherlands illustrated that, through the ERDO[9] association, assessing the optimisation potential of a shared repository as well as collaboration with other national programmes that have conducted more detailed research on specific host rocks could also be of interest for their national programme.

[9] Association for Multinational Radioactive Waste Solutions, https://www.erdo.org/

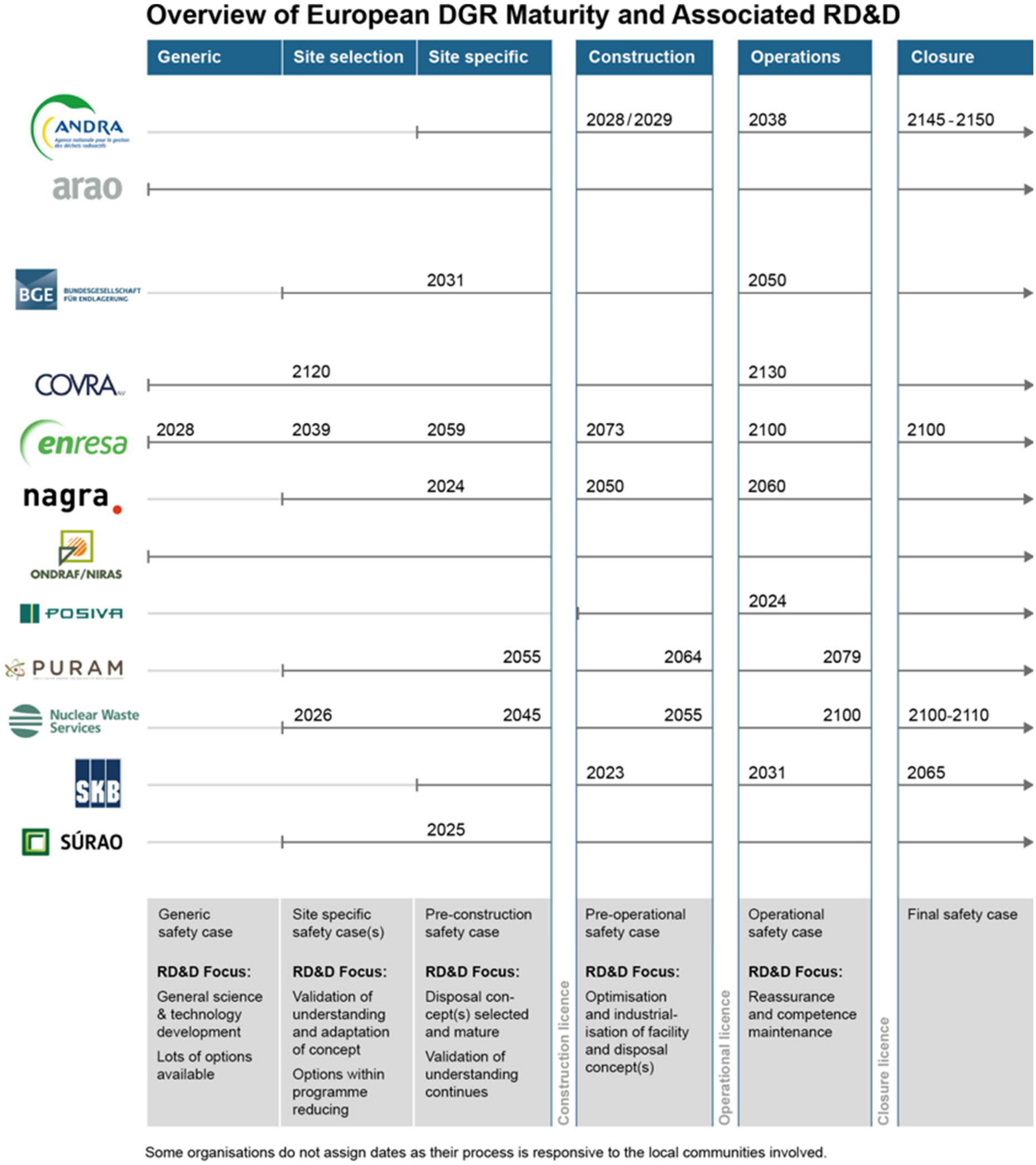

Figure 3: Approximate schedule and phase status of geological disposal programmes of selected European implementers (as of January 2023).

3. Technology and material optimisation: lessons learned and future opportunities

Disposal projects may take a century from planning until closure, and there is a continuous need for optimisation of the facilities and concepts (design and dimensioning, site investigation methods, construction methods and materials), including related components such as the waste form (e.g. new fuel types), waste packages, buffer and backfill as well as plugs and seals.

The engineered barrier systems designed for repositories require large amounts of different raw materials for manufacturing and emplacement. With this comes the development of the entire supply chain: purchasing, logistics, quality control and storage. Excavation, emplacement and potential retrieval require unique technologies. As part of the cooperation with the European Commission's Euratom R&D programme, demonstrations within underground research laboratories and with prototype equipment and machinery have provided deep insight into large-scale system performance and post-closure safety as well as into the role of laboratory and modelling work. Examples of such international collaboration projects include the Prototype Repository[10], FEBEX[11], ESDRED[12], Lucoex[13], DOPAS[14], CeBaMa[15], etc. These allowed establishing European-wide trust and confidence that disposal systems can be constructed, and that safety performance can be evaluated. The demonstrations also provided transparency about the challenges facing disposal programmes and as such have contributed to establishing public confidence. The outcomes of these projects are shared with all stakeholders and within the public domain and help to establish an excellent starting point for national programmes that are still at an earlier stage.

Especially for advanced programmes, optimising costs, time schedules and resources become increasingly relevant as the implementation phase approaches. The Finnish example shows the achievements after decades of optimisation work on the design of engineered barrier systems (EBS) consisting of clay components (segmented buffers, granular backfill, mixture of crushed rock and bentonite in central tunnels) (Figure 4).

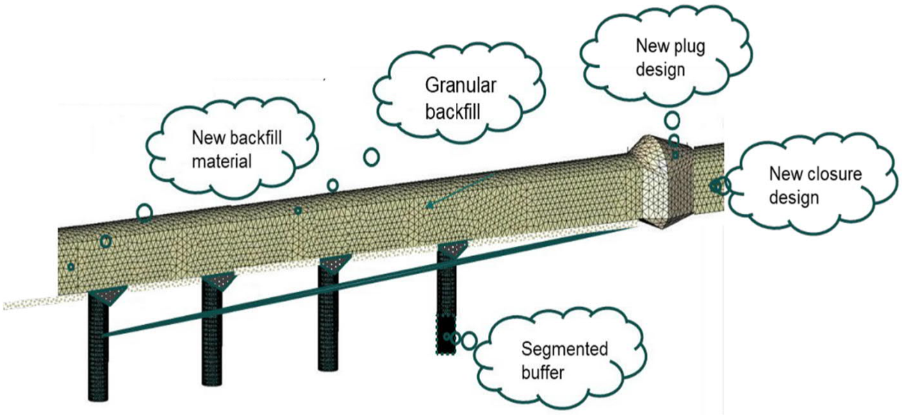

Figure 4: EBS components underwent a number of changes in the course of updating the design for the application for the operating licence (Figure courtesy of Posiva Oy)

The Finnish programme also shows how the different boundary conditions will require further attention in several stages of the disposal programme. Conservative design might be robust in the safety case, but more

10 Prototype Repository – Full Scale Testing of the KBS-3 Concept for High-Level Radioactive Waste (2000-2004), https://cordis.europa.eu/project/id/FIKW-CT-2000-00055
11 Full-scale Engineered Barriers Experiment in Crystalline Host Rock, Phase II (2000-2004), https://cordis.europa.eu/project/id/FIKW-CT-2000-00016
12 Engineering Studies and Demonstrations of Repository Designs (2004-2009), https://cordis.europa.eu/project/id/508851
13 Large Underground Concept Experiments (2011-2015), https://cordis.europa.eu/project/id/269905
14 Full Scale Demonstration of Plugs and Seals (2012-2016), https://cordis.europa.eu/project/id/323273
15 Cement-based Materials, Properties, Evolution, Barrier Functions (2015-2019), https://cordis.europa.eu/project/id/662147

concrete and specific assumptions are needed for industrial solutions. As advanced programmes are pioneers in this matter, coordination and support between waste management organisations are essential. There is a common need for strategies on how to share the workload and how to enable knowledge transfer between organisations and future generations.

The current scope and objectives of the RD&D work of the advanced programmes concentrate on preparations for the operational phase, and many implementation-related aspects require intensive development. These are mainly related to the optimisation and industrialisation of concepts and processes to ensure an efficient, reliable, reproducible operational phase over the next decades. This requires high quality standards leading to the definition of many requirements for the entire supply chain. It permits the respective organisation to design, construct and operate its disposal facility by ensuring safety without compromising the site.

Again, referring to more advanced programmes, value engineering as successfully applied in Sweden by SKB has resulted in the optimisation of technologies and materials. A further example for value engineering is the thermal optimisation of the repository design that is currently being conducted by France (Andra) to minimise the repository footprint. The approach taken relies strongly on reducing the uncertainties in the host rock parameters to the greatest extent possible and on improved process understanding at different scales (e.g., through a detailed estimation of the Young modulus variation in the Callovo-Oxfordian host rock).

Value engineering is already being applied for low- and intermediate-level waste disposal facilities. A good example is the disposal system optimisation for the L&ILW repository at Bátaapáti, Hungary, where it was applied for developing a new disposal system that was evaluated by a numerical method (based on the dose calculations).

Material optimisation is also highly relevant for early-stage programmes as it can take several decades to make final decisions regarding the engineered barrier materials. Practical examples are the design of HLW canisters where progress in science and technology is expected to lead to increased canister lifetimes and where novel materials are being investigated for various in-situ conditions. Emerging materials for other engineered barriers are also being developed, for instance aiming at lowering the steel content or alleviating construction convergence.

Reducing the impact at the source is an important optimisation principle and actions prior to disposal are key. They include improving knowledge on the waste forms and their packaging and the impact on disposability as well as studying innovative conditioning routes for specific low and intermediate level wastes.

4. Holistic, multi-stakeholder optimisation approaches for geological disposal optimisation

Classical optimisation studies focus on specific subsystems of waste management systems, such as repository operation. Furthermore, many studies have focused on a single objective of interest, such as temperature evolution during post-closure, the duration of repository operation or also cost. Hence, the goal is to improve a single aspect rather than to find an optimum compromise between potentially conflicting objectives. Few optimisation applications take a holistic approach, which covers all dimensions of the geological repository and the corresponding implementation activities and post-closure safety functions as well as the required pre-disposal activities and facilities, including the interactions between them. In holistic optimisation methods, large parts of the disposal chains are optimised together. This can apply to part of the pre-disposal chain such as packaging, waste allocation and transport as well as to the part of the disposal chain such as the design of the repository. Approaches that cover the entire chain are emerging. These methods must be able to deal with the highly complex multi-faceted aspects of optimisation. Furthermore, good insights into constraints (e.g., the description and evolution of the inventory and the logistics, the geological location and properties of the site, and restrictions in land use or transport) must be available.

Holistic methods can be broadly split into two categories. The first category largely relies on expert elicitation techniques. These can be supported by various tools, such as optimisation tools and others.

For early-stage programmes, optioneering (comparing a range of options) has been applied. An optioneering assessment methodology is an approach that determines how well an option performs when it is compared based on a scoring system. ONDRAF/NIRAS in Belgium applied optioneering to assess the impact of the length of the emplacement galleries by applying multiple criteria such as post-closure safety and operational safety, technology readiness levels, accidents/failures, reversibility, cost, etc.

For more advanced programmes, value engineering, which refers to the systematic method of improving the value of a product that a project creates, can be helpful. It is used to analyse a system that determines the best approach to managing important functions while reducing the cost. SKB in Sweden demonstrated in 2020 how value engineering can be successfully applied to mitigate the increasing costs of the planned repository for spent fuel through optimisation of the buildings, improved logistics in the supply chain and adaptation of buffer rings an engineered barrier component (Figure 5).

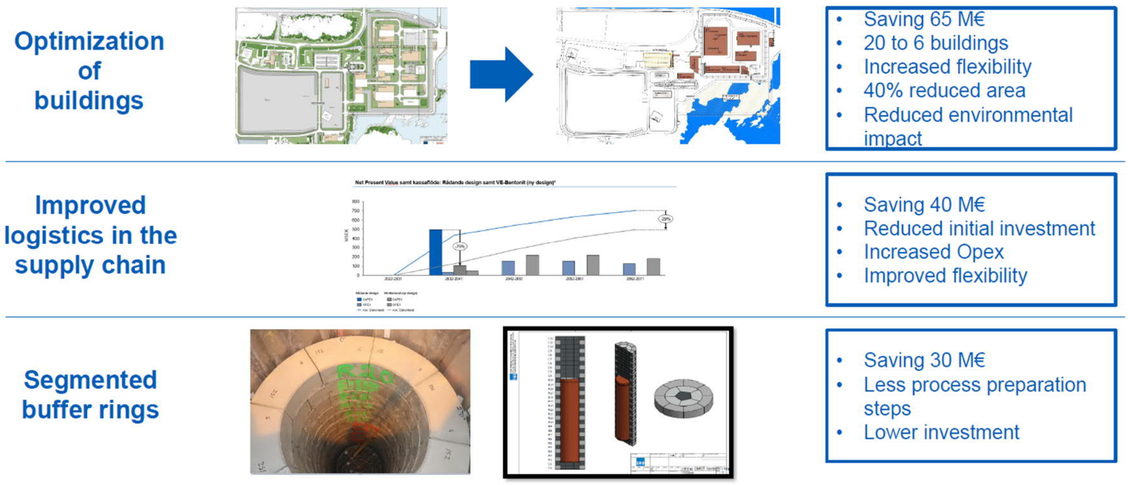

Figure 5: Value Engineering: examples of major results from SKB's optimisation (courtesy of SKB)

The second category relies mainly on numerical methods. These still require a significant expert input and, here, rely on mathematical abstractions of the description of (part of the) the disposal chain.

According to conventional mathematical optimisation theory, the objectives of different stakeholders, or rather appropriate indicators thereof, are combined to form a single objective function. This objective function is expressed in terms of several design variables that reflect the major degrees of freedom in the engineering process. For a complex endeavour such as a geological disposal facility, the conventional optimisation approach on a system-wide level is currently unfeasible. This is because the setup of the objective function and the most important constraints would require the implementation of numerous parameters and processes with very different spatial and temporal scales into a single model. This is far beyond current modelling capabilities and, even if it was not, the optimisation process would be a black box for virtually all stakeholders.

An alternative numerical approach is based on generating a large number of forward calculations using a set of proxy models to bring out the optimisation potential. One of the first simplified applications of this is the repository optimisation workflow (ROWO) developed by Nagra/CSD Engineers in Switzerland. It can operate in a multi-objective and cross-discipline setting, while aiming to be practical, efficient and transparent at the same time (Figure 6). To combine these conflicting aims in the best possible way, the approach adopted consists of using separate and rather simple models for assessing individual configurations against different objectives and corresponding indicators. The respective assessment results for many configurations are then evaluated by means of the so-called Pareto analysis technique, providing insight in the optimisation potential.

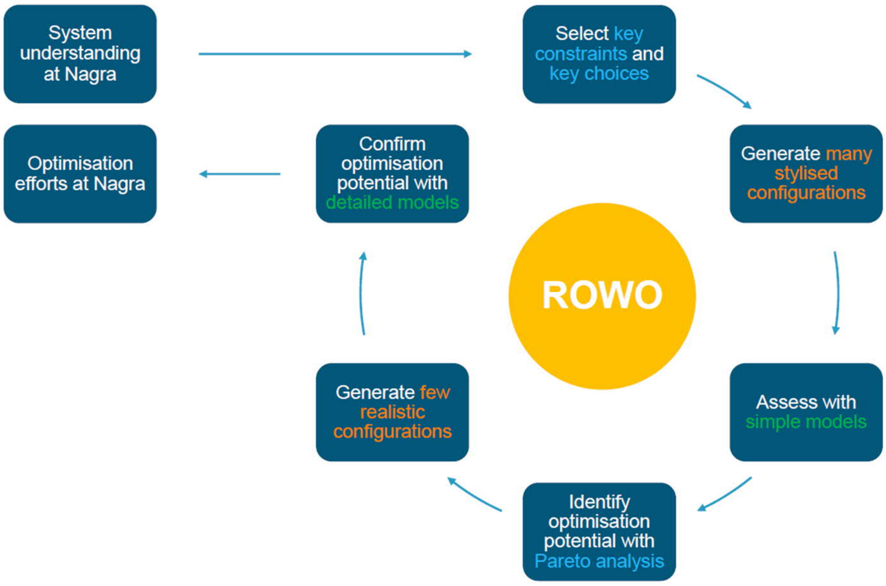

Figure 6: Repository Optimisation Workflow (ROWO) – Approach (Nagra/CSD Engineers)

The two categories used to address holistic and multi-stakeholder optimisation cannot be strictly separated, and, very often, optimisation approaches rely on a combination of both expert elicitation and numerical tool support in one way or another.

5. Lessons learned from optimisation in other industries relevant for geological disposal

The safe construction, operation and closure of a geological disposal facility is a nationally significant infrastructure project for which many design-optimisation lessons can be learned from non-nuclear (conventional) infrastructure developments. Nuclear and radiological safety are ensured through multiple and diverse barriers working in synergy, however, much of the complexity and project risk in geological disposal facility development is associated with constraints and uncertainties that are not directly related to the end-use of the facility. Construction safety, geological uncertainty and social acceptability are examples of considerations where learning from conventional infrastructure projects such as the Prague City Ring Road (SATRA, Czech Republic) can provide valuable insights. Such developments provide operational feedback on the use of integrated control systems, automated monitoring and fire and ventilation systems, which can support value engineering in geological disposal facility development (Figure 7).

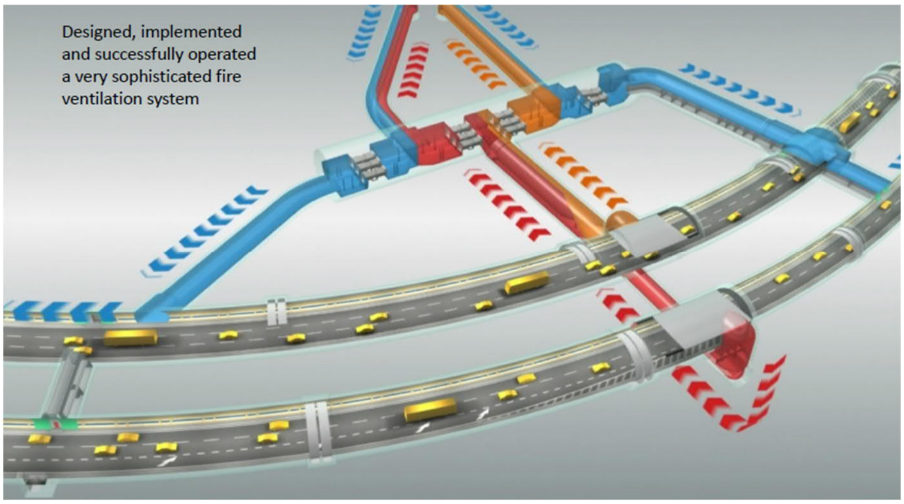

Figure 7: The Blanka tunnel complex–unique technical solution in Czech Republic (courtesy of SATRA, modified)

In nuclear-related projects, it is important to address the needs of decision-makers and local communities as well as the need to provide scientific evidence and underpinning knowledge to satisfy radiation protection and environmental regulators. Optimisation of facility design can therefore be complicated by numerous competing demands. The development of sponsor and system requirements is a key tool in controlling complex systems such as a geological disposal facility. Systems engineering tools such as requirements trading allow implementers to balance potentially competing demands on system attributes when optimising the repository design. In nuclear facility decommissioning projects such as the former Trawsfynydd Nuclear Power Station in Wales, optioneering proved a useful discipline in identifying those attributes which differentiate them, with a focus on addressing highest-level decisions first.

In addition to identifying requirements, discerning critical success factors is a further tool that can support optimisation in the design of highly complex, interdisciplinary, long-term, high-investment projects of public interest. Such critical success factors are important in shaping the developer's commercial strategy, and consequently de-risking the project. Shared critical success factors ensure cooperation between the client and supply chain through a shared understanding of what defines success as they collaborate in optimising the facility's design. Critical success factors may relate to quality and functionality, health and safety, environment, public acceptability, organisational stability and process efficiency, schedule or cost (Figure 8). For example, in the Gotthard Base Tunnel construction project in Switzerland, re-use of all excavated material was set as a critical success factor for environmental sustainability. In this project, competing options were assessed by a suitably experienced team against a set of critical success factors using the 7-point Likert scale (strongly disagree; disagree; somewhat disagree; neither agree nor disagree; somewhat agree; agree; strongly agree). This simple approach also enabled recognition of solutions resulting in over-achievement.

Figure 8: Success factors - derived from various project histories (courtesy of Heinz Ehrbar Partners)

Optimisation of the design of a disposal facility regarding factors such as societally acceptable urban design and reduction of environmental impact is an important consideration in maintaining the support of local communities for all major infrastructure projects. Moreover, development of broader benefits to local society through the associated development of local facilities such as transport infrastructure, flood defences, community facilities, visitors' centres and apprenticeship programmes reinforces the long-term commitment of the disposal facility project to the community. The appropriate selection of requirements and critical success factors can provide a structured approach to ensure such considerations are accommodated.

6. Overall conclusions and outlook

The term optimisation in the context of implementing geological disposal facilities has widened from focussing initially on post-closure nuclear safety to many other aspects (e.g., design, engineering, cost, environment, acceptance). There is a consensus that optimisation thinking should take place from the start of the implementation of the disposal programme as key decisions must be made at this stage. Avoiding the construction of an excess nuclear facility by co-locating different inventories can be the ultimate optimisation from both a safety and an engineering point-of-view. Once the decision to construct a disposal facility has been made, based on the national legal context and relying on experience from advanced programmes, optimisation efforts must be included from the start of the project (and site selection is at the core of this). This requires defining where key optimisation potential lies and estimating the lead time required to evaluate it, such that when a final decision is due, interests can be weighed and decision-making is transparent. A disposal programme roadmap is an important instrument in this as it defines the milestones and the requirements needed to achieve the milestones. From that the activities and developments needed can be derived. As a result, it is possible to focus primarily on the important optimisation opportunities, rather than optimising aspects in detail that might still be subject to major changes in the future. Making the trade-off visible and providing full transparency to demonstrate and avoid undesirable impacts especially with respect to operational and post-closure safety are essential components of the optimisation process.

Exploration and testing of novel materials and technologies

As decision-making continues over several decades and materials and technologies advance rapidly, implementers are advised to periodically review the potential for further refinement of safety-relevant analysis, reduction of over-conservatism and replacement of existing materials and technologies with higher, or equally-performing ones. In this context, safety, cost and environmental impact are by no means naturally competing interests.

Digital environments and evaluation tools to support optimisation

The complexity of the optimisation process requires a clear decision basis and tools at hand that bring out the optimisation potential in each stage of the programme. Several tools are available, and these are likely to evolve with the stage of the disposal programme. Initially expert elicitation and simple numerical support models (e.g., optioneering) are required to make fundamental decisions. Once insight is available on the size of the inventory, the repository site and the potential multi-barrier concepts, selected advanced tools and processes capable of evaluating large parts of or even the entire disposal chain are very welcome. At this later stage, integrating tools from various domains (e.g., Building Information Modelling (BIM) and 3D geological models) is expected to be of great benefit. Once the detailed design is in place, optimisation tools will show important similarities with the environments used for the classical optimisation of large infrastructure projects (e.g., value engineering). At this final stage, the entire supply chain becomes part of the optimisation process.

Especially for programmes in the earlier stages that will not be operational for several decades to come, the ongoing digital transition offers major opportunities for enhancing the optimisation process. The possibility to generate virtual adaptations to the reference concept or to the design of the geological disposal facility and evaluate these in terms of safety, practicality and (although less easy) acceptance in a short timeframe will be a major step forward. The development of digital twins at the repository scale is only a part of this process. More progress in machine learning and proxy model development are needed, but first applications are already emerging. Holistic assessment approaches, i.e., assessing large parts of or even the entire disposal chain, are currently being tested and hold promise in the context of life-cycle assessments. Further significant investment is needed in all these domains.

Learning from other industries with respect to optimisation

Optimisation, especially when going hand-in-hand with digitalisation, is taking place in many domains of society, and initiatives that cut across geological disposal and other uses of the subsurface (carbon storage, geothermal applications) or across the wider nuclear domain (pre-disposal, decommissioning) are to be welcomed.

Looking at the pioneers in the implementation of geological disposal (Finland, Sweden, France), it becomes clear that optimisation towards the operating phase requires a major effort and many lessons remain to be learned and shared. The optimal acquisition of experience from others is needed to maintain competences and avoid duplicating work, and to the extent permitted within the legal context, commercial services can play an important role.

To address the topics discussed above as well as other RD&D optimisation needs, the European Joint Programming (EURAD-1 and future EURAD-2), the IGD-TP and bilateral collaborations provide clear routes. Outcomes of the various projects will support the optimisation efforts of all the waste management organisations involved and thus the progress in implementing geological disposal globally.