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Database application for multi-level area-specific FEP catalogues in the German site selection process for high-level radioactive waste disposal

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Abstract. The safety case for a nuclear waste repository requires the consideration of future evolutions. Methodology and technical implementation for the systematic derivation of a limited number of expected and deviating future evolutions of potential repository siting areas are presented. Evolutions are derived from the analysis of FEP (features, events, and processes) catalogues, which are comprehensive, structured descriptions of a repository system and the interactions and dependencies of processes and components within the repository. In order to apply this work-intensive method to the ninety sub-areas which are currently under consideration in the Site Selection Procedure for the final disposal of high-level radioactive waste in Germany, a generic FEP catalogue is compiled in a first step, from which host rock-specific and area-specific FEP catalogues are created. An analysis of component and process interactions is completed at host-rock level and then transferred and adapted to individual areas, taking site-specific information into account. To facilitate the documentation and analysis of the disposal system and ensure consistency, a sophisticated in-house database solution has been developed.

1 Introduction

The Federal Company for Radioactive Waste Disposal (BGE) is the German waste management organization responsible for identifying the site with the best-possible safety for the deep geological disposal of high-level radioactive waste. The Site Selection Procedure consists of three phases with an increasing level of detail, according to the Repository Site Selection Act (StandAG, 2017). Step 1 of Phase I was completed in September 2020 (BGE, 2020). Ninety sub-areas were identified that are expected to have favorable geological conditions for safe disposal. The potentially suitable sub-areas cover approximately 54 % of Germany and are located in three different host rocks: rock salt (halite), claystone, and crystalline rock.

Step 2 of Phase I is currently in progress and includes the so-called representative preliminary safety analyses that aim to assess the extent to which the safe containment of the radioactive waste can be expected (for details see Hoyer et al., 2021). They are performed according to the Disposal Safety Requirements Ordinance and the Disposal Safety Analysis Ordinance (EndlSiAnfV, 2020; EndlSiUntV, 2020). Step 2 of Phase I will end with the identification of siting regions that are candidates for surface exploration.

Within the preliminary safety assessments, the behavior of the disposal system is analyzed in its entirety with regard to the safe containment of the radioactive waste, across all operational phases of the repository. The actual behavior of the repository system cannot be predicted for the entire assessment period of one million years, thus analysis of a limited number of expected and deviating evolutions (scenarios) needs to cover what could happen in the future. Since the first transfer of the scenario methodology from policy strategy development to nuclear waste disposal (Cranwell et al., 1990), the method has become a standard instrument in the development of a safety case (IAEA, 2012).

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The key system component for assessing safe containment is the "area of host rock with a barrier function". Through the application of various safety oriented criteria in the representative preliminary safety assessments, this area is incrementally reduced from an entire stratigraphic formation to a particular geometry, analyzed as a potential siting region. Safe containment needs to be demonstrated for the expected evolution.

Evolutions are derived systematically from the analysis of FEP catalogues (features, events, and processes), which are comprehensive, structured descriptions of a repository system and the interactions and dependencies of processes and components within it. FEP catalogues are an established tool in scenario analysis for nuclear waste disposal (Smith et al., 2016). Many FEP catalogues for nuclear waste disposal in different host rocks already exist, either for national projects (e.g. Wolf et al., 2012; SKB, 2010; Nagra, 2002) or as international reference works such as Freeze et al. (2020). However, the current challenge in the German site selection procedure is to handle multiple host rock settings (claystone, crystalline rock, and rock salt, both in a steep deposit and stratiform deposit) as well as a large number of areas at once. There is no precedent for applying the established tools and methods to this number of host rocks and areas concurrently to the level of detail required by the regulations. This paper presents a methodology to tackle this workload and to guarantee internal consistency of the assessment by utilizing multi-level FEP catalogues that build on each other. The starting point is a moderately sized generic FEP catalogue with a few key simplifications. A database serves as both data storage as well as providing an interface for the analysis workflow that ultimately reduces workload.

2 Methodology and technical implementation

2.1 Multi-level FEP catalogues

A generic FEP catalogue (hereafter referred to as FEP catalogue Site Selection) was compiled first, from which host rock-specific and area-specific FEP catalogues are derived (Fig. 1).

2.1.1 FEP catalogue Site Selection

The FEP catalogue covers the characterizing features of the disposal system, here referred to as *components* and their *properties*, as well as events and processes, which are summarized as *processes* acting in and on the disposal system. The Safety Analyses Ordinance (EndlSiUntV) allows some simplifications for the representative preliminary safety assessments within the current phase of the Site Selection procedure:

- focus on geogenic processes (originating in the geosphere independently from the repository)
- assume that (geo-)technical barriers perform as intended (provided that this does not appear impossible according to the current state of the art in science and technology).

Additional framework conditions set by BGE are the climate development (glacial cycles of 100 000 years) and the tectonic setting (continuation of current stress field). The FEP catalogue Site Selection contains 21 geogenic processes, 22 technogenic and small scale processes, three geological components with up to five properties, and eight (geo-)technical components with two properties, respectively. Each process and component entry has a brief definition and a description. Components are described in such a generic way that they can be used for all host rock settings. Properties in the FEP catalogue Site Selection are actually groups of properties, for example the "mechanical properties" cover density, strength, deformation capacity, stress and structural heterogeneity (discontinuities and fractures). Some related processes with less relevance for the representative preliminary safety assessments, particularly those acting within the repository, were combined to reduce the overall number of processes. The list of processes and components and the grouping and description of properties are derived from Capouet et al. (2019, 2024), Stark et al. (2016a, b), and Mrugalla et al. (2020).

2.1.2 FEP catalogue Host Rock

Following the FEP catalogue Site Selection, its elements are used to derive a geological FEP catalogue for each host rock setting (claystone, rock salt, crystalline rock) containing all geogenic processes and geological components. Additionally, a technical FEP catalogue, containing all technogenic and small scale processes as well as all components, is derived for each host rock. All sub-areas of one host rock are conceptually treated as one large, non-contiguous, heterogeneous area. Within the FEP catalogue, each process is characterized by an *occurrence* which is classified by one of three levels of (qualitative) probability: "plausible", "not to be ruled out" and "ruled out". For each process that is "plausible" or "not to be ruled out" the *intensity* is estimated, classified by two levels of (qualitative) probability: "expected" and "possible". While the "expected" intensity describes the most likely scenario, "possible" intensities are optional and account for uncertainties, for example the amount of erosion. The definition of occurrence and intensities for each process decide whether the process is part of the expected or the deviating evolutions of the repository (Fig. 2). Only plausible processes in their expected intensity are part of the expected evolution, everything else is used to derive deviating evolutions. Less likely "possible" intensities for processes "not to be ruled out" are not considered. The assessment period is subdivided into four time intervals: (1) Thermal phase (characterized by heat generation from the emplaced waste), (2) remaining interglacial, (3) first glacial pe-

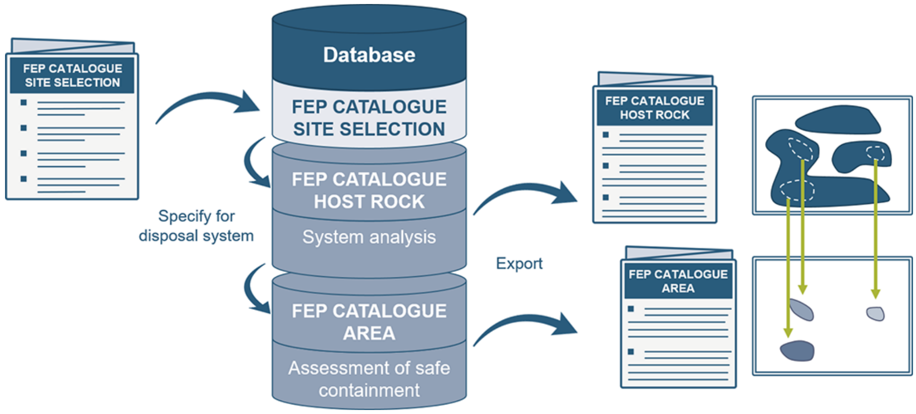

Figure 1. Three levels of FEP catalogues are created for the representative preliminary safety analyses. All FEP catalogues are also exported to documents for archival purposes. On the right is a schematic relating sub-areas of one host rock (top) to areas analyzed as potential siting regions (bottom).

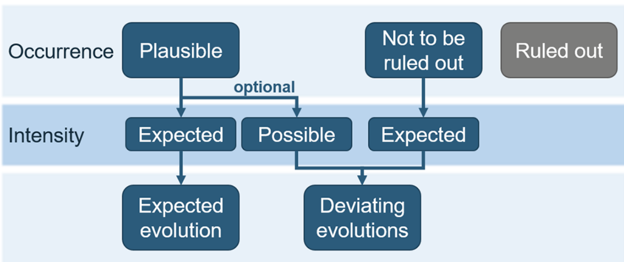

Figure 2. The definition of occurrence and intensities for each process decide whether the process is part of the expected or the deviating evolutions of the repository.

riod (after 100 000 years, beginning with continuous permafrost), (4) remaining assessment period. In total ten recurring glacial/interglacial cycles are expected for the assessment period. The processes in the FEP catalogue are connected to one or more of these time intervals.

An analysis of first order interactions between components and processes is completed within each FEP catalogue: how each process acts on each component property, and how each component property acts on each process in turn. Both positive findings (i.e. an interaction happens) and negative findings (i.e. no interaction happens) are documented and characterized. This method builds on the work of Stark et al. (2016b).

The geological FEP catalogue is then analyzed for second order interactions. Second order interactions describe how a process can be influenced by other processes changing component properties and how a process changing component properties influences other processes. Not all second order interactions are physically viable and require a description (e.g. erosion changes the geometry of the overburden, the changed geometry has no influence on the expected intensity of magmatism). All other second order interactions are evaluated regarding their influence on the disposal system; only such second order interactions that could potentially impact the assessment of safe containment are marked for further analysis (e.g. erosion changes the geometry of the overburden, the changed geometry could lead to subrosion in strata that were unaffected before). A relevance is assigned to each of these interactions as described in Chapman et al. (1995). In a final step, the influence of each process on the safety functions is briefly described. It has to be noted that the representative preliminary safety assessments rely strongly on rough approximations, the use of analogues, and expert judgement. Many processes that will likely be included in models in future, more detailed, safety assessments have to be appraised through literature research and are therefore represented as the sum of their actions in the system. For example, the impact of changing properties in the geosphere on the erosional capacity of subglacial tunnel valleys cannot be judged in detail, and so only the initial estimate of tunnel valley depth (from Breuer et al., 2023) is carried through the assessment. The only exception is erosion, which changes the geometry of the overburden and can lead to a deeper erosive level of the potential tunnel valleys: these processes can add up. For this reason, feedback loops (a process acting on a property, which influences the same process in turn) are not characterized.

2.1.3 FEP catalogue Area

The analysis of the geological FEP catalogues is then transferred and adapted to individual areas, considering site-specific information for assessing safe containment within each "area of host rock with a barrier function". Because process intensities and process-property interactions are described for the maximum intensity projected for all sub-areas of one host rock at the generic level, any single area in particular is likely to experience fewer processes at lower intensity. In many cases, the "area of host rock with a barrier function" is already reduced due to safety oriented criteria applied before this step of the assessment. This also means that the number of relevant first and second order interactions generally decreases, especially when the top surface of the "area of host rock with a barrier function" has been defined deeper below ground surface.

2.2 Database application

To facilitate the documentation and analysis of the disposal system and ensure consistency, a sophisticated in-house database solution has been developed. The relationships of processes and component properties in the FEP catalogue are mapped and stored in a relational database. The database is accessible through a user-friendly web application. This approach guarantees data integrity, reproducibility, and usability and accelerates the evaluation process by employing automation where applicable.

2.2.1 Technical challenge

There are 12 component properties (across three components) and 21 geogenic processes, resulting in at least 504 first order interactions per system. In addition, due to uncertainty, multiple degrees of intensity have to be considered for some processes. There are at least 10 584 possible second order interactions. The high number of evaluations and descriptions for each system, compounded by the also large number of systems (projected to between 50 and 100), necessitates an accessible, clear documentation that also provides a structured workflow.

2.2.2 Software implementation

While first prototypes were developed in Microsoft Access, the working version of the database is now an internally hosted web application. The python web framework Django (Django Software Foundation, 2024) is used for back end-data and security management. Data is stored in a relational MSSQL database. Display of the front-end happens mainly as static content served via HTML and customized Bulma CSS (Thomas, 2024), with selected content being provided dynamically with several JavaScript libraries: TabulatorJS (Folkerd, 2024), AntV G6 (Ant Group, 2024), Alpine (Alpine.js, 2023), htmx (Big Sky Software, 2024) to improve user experience. Authentication is handled via the BGE-internal active directory.

2.2.3 Functionalities

Besides basic authentication to access the web application, there are several authorization layers to customize the individual access and rights of every user. The application allows for the tracking of the work status of each FEP catalogue, as well as the tracking of all changes made for every entry as part of its version control. It has the option to copy existing FEP catalogues to varying degrees of depth. This allows for a simplified workflow as area-specific FEP catalogues can be created as copies of the respective host rock-specific FEP catalogue and subsequent changes in the copy are highlighted. The interface is also able to process basic text formatting, and has a module connecting to the literature management software Citavi, enabling citations within the application. These features are integrated as part of an MS Word export functionality, as every FEP catalogue (i.e. the system analysis for each host rock and each area) is exported to MS Word to become part of the larger documentation of the siting region proposal and archiving efforts of the Site Selection Procedure. After publication of a specific FEP catalogue, its data is locked from further changes.

Some processes have geographical limits (ice sheet cover, marine transgression, etc.). These are stored separately and evaluated for the assessment areas in ArcGIS Pro.

2.2.4 Visualization

Graph plots visualize the process-property interactions that have been deemed relevant to the performance assessment. For each process, the effect the process has on properties and subsequent effects on other processes are shown (Fig. 3a). The graph can be reversed, so that the effects of properties changed by other processes on the process in question are shown (Fig. 3b). If a process has multiple intensities assigned, all are shown separately (e.g. erosion in Fig. 3b). Within the web-application, it is possible to navigate to the description of the intensity and their own graphs for the right hand processes in Fig. 3a, and the left hand processes in Fig. 3b respectively. From the representations of the component properties the interactions tables can be accessed.

3 Results

The methodology and database create a lucid workflow that enables systematic handling of process-component-interactions for a moderate number of processes and components and a large number of areas. The resulting workflow is shown in Fig. 4. This is applied fully to the geological FEP catalogues. For the (geo-)technical FEP catalogues created at host rock level, the workflow stops at the first order interactions.

Taking subglacial tunnel valley erosion as an example for a process, the FEP catalogue Site Selection gives a definition and description of this process (Müller et al., 2023). Subglacial tunnel valleys were observed in several sub-areas of the host rock claystone. Therefore, their occurrence is classified as "plausible" in the host rock specific FEP catalogue and linked to two of the four time intervals: interval 3 (first glacial period) and interval 4 (remaining assessment period). The "expected" intensity of the process is characterized as meltwater driven channelized erosion reaching up to 600 m below ground surface, with the valley being mostly filled

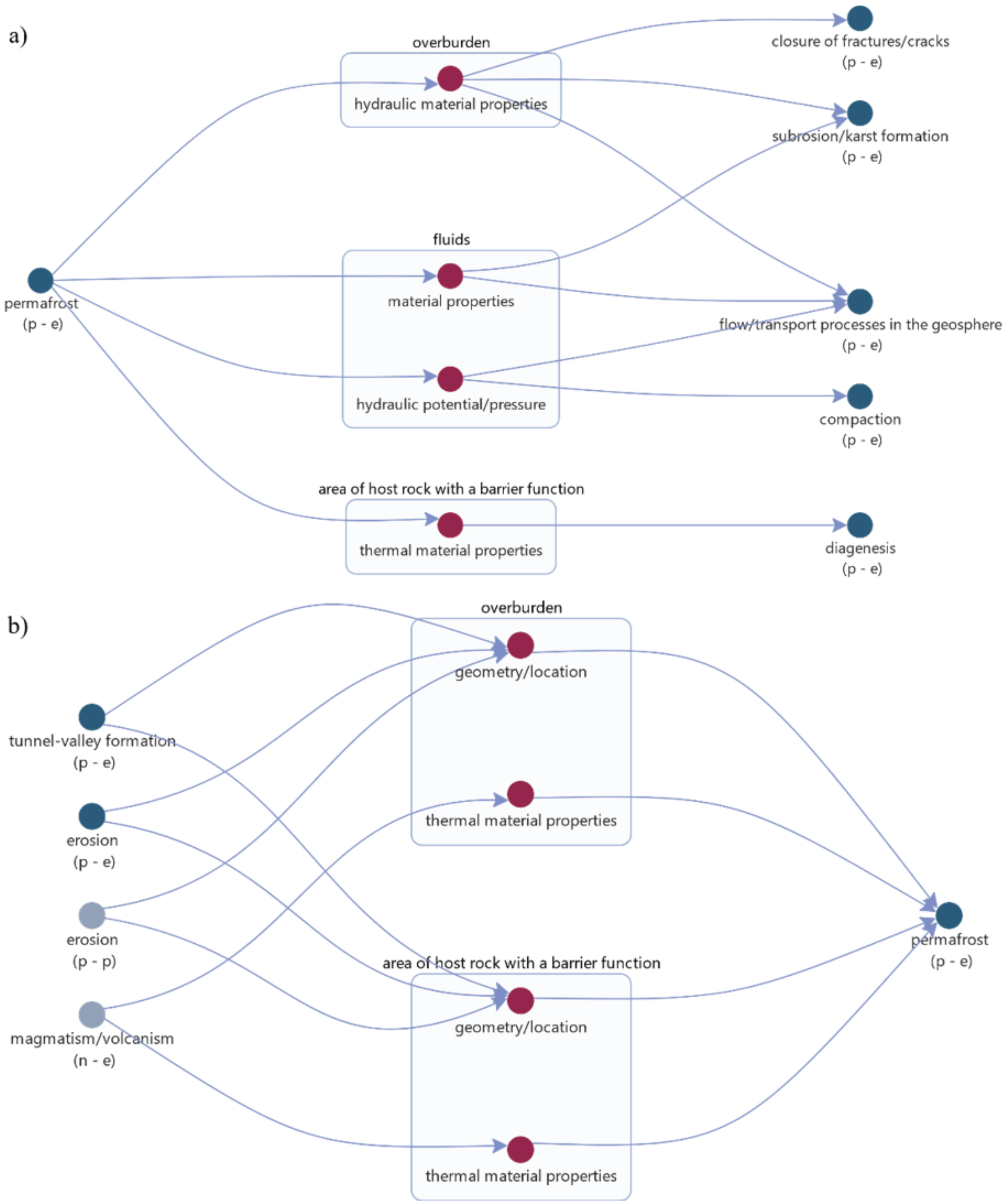

Figure 3. Interactions between processes and component properties are visualized as graphs. The boxes represent components, the nodes within are the associated properties. Shown here are the effects of permafrost **(a)**, and the actions on permafrost **(b)** as they are determined for the host rock catalogue for claystone. Letters in brackets indicate occurrence and intensity, "p–e" for "plausible – expected". In **(b)**, erosion is represented twice, with both an expected and a possible intensity. Magmatism/volcanism has an occurrence of "not to be ruled out".

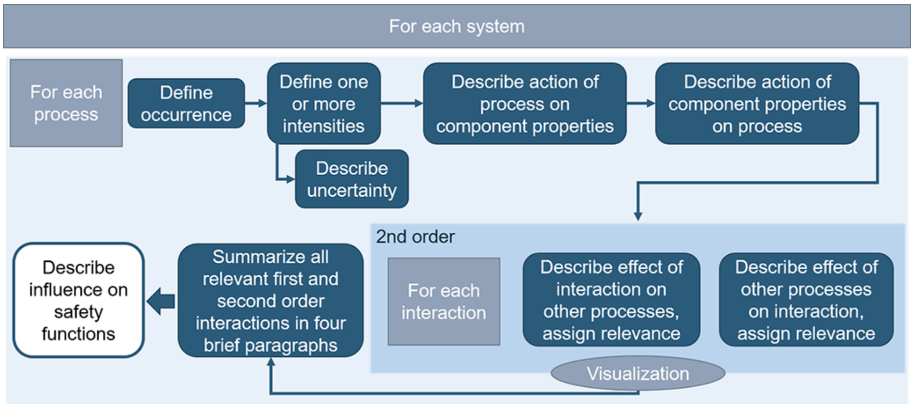

Figure 4. FEP catalogue workflow for a single repository system.

with sediment before the next glacial (Breuer et al., 2023). The depth of erosion has a lateral zonation based on observations of past tunnel valleys (Breuer et al., 2023). The interactions of the process with the properties of the "area of host rock with a barrier function" and its overburden (two geological components) are described. Viewed at this level, tunnel valley erosion can change the *geometry* of the "area of host rock with a barrier function" by cutting through the entire overburden and more.

Figure 5 exemplifies the interactions between processes and components with their properties that are used to derive evolutions over 1 million years. The left panel shows the initial state of an area. The middle panel illustrates interactions between features and processes. The property "geometry/spatial position" of the overburden is influenced by multiple processes. In addition to tunnel valley erosion, fluvial erosion and denudation also affect the overburden, e.g. by lowering the land surface and thus reducing the thickness of the overburden, which is part of the property group "geometry/spatial position". The right panel shows how processes superimpose. After fluvial erosion and denudation lowered the land surface, subsequent subglacial tunnel valleys may cut deeper into the subsurface. The processes subglacial tunnel valley erosion and fluvial erosion/denudation considered on their own may not reach far enough into the subsurface to endanger safe containment. The combination or superposition of both processes, however, has a larger reach and may influence the safety functions of the repository system.

When narrowing down to the area specific FEP catalogues, the classifications and interactions are re-evaluated. In areas that were not covered by glaciers in the past, the occurrence of subglacial tunnel valley erosion might be classified as "not to be ruled out" or even "to be ruled out", depending on local circumstances. In areas assessed as potential siting regions, tunnel valley erosion can not reach the "area of host rock with a barrier function" because it is now defined deeper underground than before due to the application of safety oriented criteria, increasing the effective overburden.

The host rock catalogues have already been completed and several areas from each host rock have been assessed. The method as shown here has proven to be reliable insofar as a process based on expert judgement can be called reliable. Since the descriptions at host rock level were derived from collaborative discussion, single areas can now be handled by a single operator. The information held in the FEP catalogue for each assessment area can then be used in a qualitative evaluation of safe containment.

The definitions of processes, components and properties were subjected to external quality control. The interactions between processes and component properties were defined collaboratively, including special experts where necessary. The reasoning behind all decisions is documented in the database, including literature references where applicable. All FEP-catalogues Host Rock were also subjected to external quality control. Results for each assessment area are discussed in a quality control workshop with the team in charge of the geological model, who are separate from the FEP catalogue workers.

4 Conclusion and outlook

While the representative preliminary safety assessments are still ongoing, no conclusion to the entire process can yet be drawn.

Simplifying component properties to property groups and combining some processes with less relevance for the representative preliminary safety assessments in the FEP catalogue Site Selection greatly reduced the number of potential interactions between processes and component properties. This was a very successful measure that still provided a good level of detail. Through discussion with external experts, initial misinterpretations could be mitigated by renaming processes or adjusting definitions.

Creating the FEP catalogue Site Selection instead of using a pre-existing FEP catalogue was time intensive, but it allowed these key simplifications in the list of processes

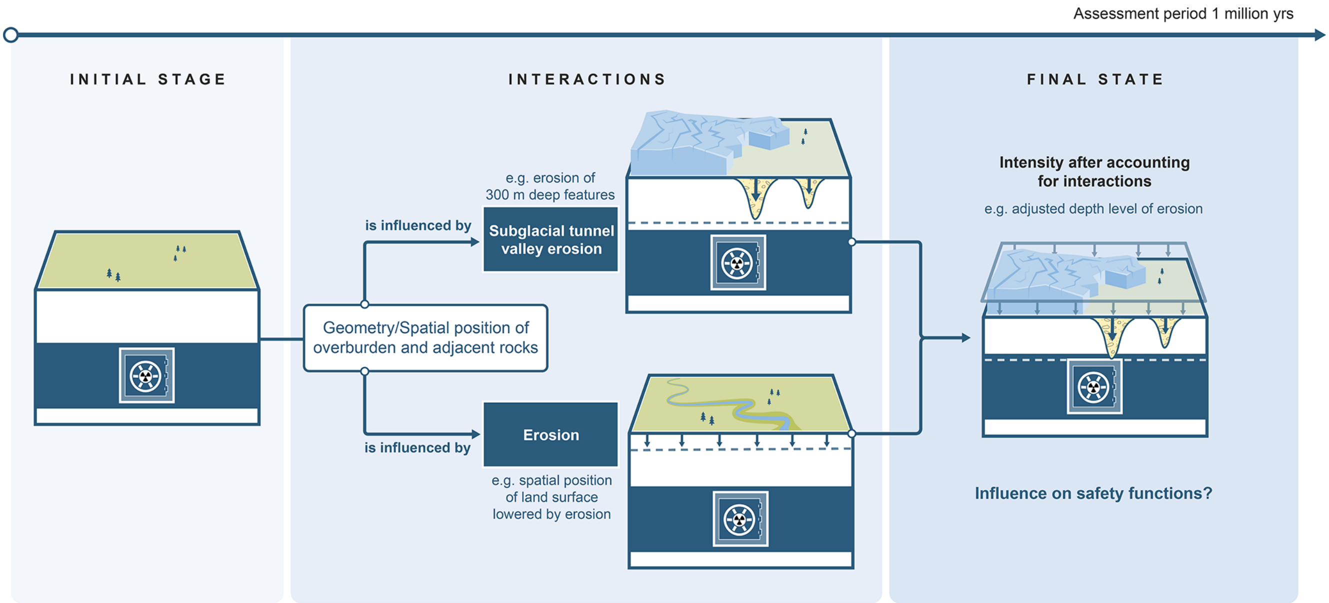

Figure 5. Example of accounting for second-order process interactions across the assessment period when evaluating influence on safety functions.

and components and their properties. It also created a native knowledge base, in the sense that the members of the working group could deepen their process understanding. While input from external experts was essential for the generic catalogue and host rock catalogues, application to single areas was possible without external input.

Setting up the database so that a full FEP catalogue with its interaction tables and associated judgements and reasoning could be copied and then modified while tracking changes was the biggest gain in efficiency. Only having to determine the differences for an area to the host rock assessment in view of local details instead of having to start a new assessment was (and is) essential.

Investing time and effort in the knowledge base at the start has made the subsequent work manageable or even possible, as the time available to assess each area is fairly short. Estimating how relevant certain FEP interactions are within the workflow further reduces the complexity of the final safety assessment by filtering out insignificant information.

The method retains the comprehensive approach of a FEP catalogue while greatly increasing efficiency in repeated applications.

The finalized FEP catalogues are intended to be published within the scope of the siting region proposal, which is scheduled end of 2027.

Future work in Phase II of the Site Selection procedure will include a much more detailed assessment of the geotechnical and small scale processes and their interactions with the repository mine components. The components of the repository will also be much more detailed, since their development will progress. The EndlSiAnfV and EndlSiUntV require much more comprehensive modelling work from the further developed preliminary assessments going forward, which needs to be tied in to a comprehensible story of the evolution of the repository system. The structured nature of the FEP catalogues as graphs offers the potential to simplify scenario development through several mathematical approaches. This may involve a range of techniques, from statistical methods, graph theory, machine-learning algorithms, all the way to high-level AI assisted evaluations. By leveraging these tools, systematic scenario development can be further automatized. The assessment of safe containment needs to be progressed from a qualitative evaluation to a model based, quantitative evaluation, that is informed by the system understanding gained from FEP catalogue analysis.

Code availability. The source code of the InfELSen database system is publicly available via Zenodo, https://doi.org/10.5281/zenodo.17305545 (Schöne et al., 2025).

Data availability. The underlying data will be published in the scope of the siting region proposal with the conclusion of the current phase of the site selection procedure, scheduled for 2027.

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