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Transdisciplinary research on the safety case for nuclear waste repositories with a special focus on uncertainties and indicators

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In the search for a repository site for high-level radioactive waste in Germany, the perception of safety and trust in the actors are central to public acceptance. In communicating safety, methods of safety assessment and the role of uncertainties need to be addressed. Given the complexity of the issue, there is a need for indicators that are suitable both for assessing the long-term safety of repositories and for communicating with the general public. Similarly, there is a requirement to communicate uncertainties in an accessible manner. The TRANSENS project provides basic research in nuclear waste management (NWM) and utilizes a transdisciplinary approach: Non-experts who are not directly affected by the site selection process and who have no stated interest in NWM are involved in the research process, as are practice actors. A series of four transdisciplinary workshops was specifically designed to explore the perspectives of individuals with a high level of disciplinary knowledge but no system knowledge of NWM. Participants were selected from doctoral students in science and technology who had no prior knowledge in this area. Two of these workshops address the questions stated above and are presented here. The article describes the considerations underlying the workshop planning and implementation phases, and the content developed in the workshops on indicator selection and visualisation of uncertainties. The participants compiled a list of desirable indicator properties, which showed a high degree of congruence with the relevant literature. A proposal for a database to collect, administer and assess uncertainties shows similarities with the approach followed by the German implementer and complements it with an interactive visualisation. Transdisciplinary work is resource-intensive and its use in a research context must be carefully considered for each individual application. A transdisciplinary approach was successfully used for the purposes of method validation, method optimisation and the development of disciplinary impulses. An application of transdisciplinary approaches for optimising the Safety Case of nuclear repositories is feasible.

KEYWORDS

nuclear waste management, radioactive waste disposal, deep geological repository, safety assessment, transdisciplinary research, science communication, data visualisation

1 Introduction

Germany's ongoing site selection process aims to identify the site with the best achievable safety for a deep geological repository for its high-level radioactive waste (Deutscher Bundestag, 2017; Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit, 2020; Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit, 2022). A description of the chosen site will ultimately be provided as part of the Safety Case. The Safety Case is a comprehensive collection of documents which forms the basis of the licensing procedure and comprises all arguments supporting the suitability of the (as yet undefined) disposal concept, including site description, repository design and safety analyses. At the same time, it aids the understanding of the repository system and the processes that take place in it, and helps to refine potential future developments. The Safety Case is therefore both method and report. Its substantial technical content is aimed at subject matter experts[1] (Radioactive Waste Management Committee, 2013; International Atomic Energy Agency, 2012).

The research was motivated by the requirements for transparency and public participation laid down in the German Site Selection Act: Information obtained in the course of the site selection process must be made publicly available in order to ensure that the public is kept fully and systematically informed at an early stage about, i. a., the status of its realisation and its likely impacts (Deutscher Bundestag, 2017). The wording of the regulations is broad and leaves room for interpretation. However, it is understood that the information to be provided includes the results of long-term safety analyses and the methodology used to demonstrate safety. Although not explicitly stated in the legal text, it is implied that relevant data should be prepared in such a way that it can be understood without expert knowledge.

TRANSENS is not part of this (political or public) participation process but provides basic research on nuclear waste management (NWM), including on long-term safety and the presentation of related data, with the support of non-experts. TRANSENS aims to integrate the perspectives, values and bodies of knowledge of non-experts and practice actors with academic knowledge (mode 2 transdisciplinarity). The involvement of non-experts in NWM research is still rare and primarily concerns local stakeholders. A unique feature of TRANSENS is that the non-experts involved were specifically selected *not* to be stakeholders (Seidl et al., 2024; Röhlig et al., 2021; TRANSENS, 2019); the participation of non-experts without any prior interest in NWM sets it apart from research projects such as Modern 2020. A fixed Citizens' Working Group[2] accompanies the TRANSENS project throughout its entire duration, exploring societal issues such as trust and governance, as well as contributing to technical research on topics such as two-level repositories, monitoring and retrievability. Of particular interest is research to improve the Safety Case (TRANSENS-SAFE, 2023).

In addition to workshops with the permanent Citizens' Working Group and with practice actors (Ebeling et al., 2024a), this topic was explored in a series of four workshops with participants specifically selected to represent individuals with a high degree of disciplinary knowledge, but without previous experience in NWM. Each workshop focused on a particular technical aspect and aimed to answer specific questions. Results obtained from the two workshops on features, events and processes (FEP) and scenario development are included in Ebeling et al. (2024b). The results of the remaining two workshops are presented and discussed here, and the questions they sought to address were: Which indicators should be used to assess (long-term) repository safety? How can these indicators and their associated uncertainties best be communicated to the general public?

The two workshops are jointly presented by a member of the TRANSENS research team (Martina Heiermann) and one of the workshop participants (Vinzent Olszok). After explaining the motivation for transdisciplinary research, the planning and implementation processes of the workshops are described. The results achieved by the workshop participants are presented. Selected results are discussed in order to demonstrate the application of transdisciplinary processes to method validation, method optimisation and generation of disciplinary impulses. We argue that, although the circumstances of each project and group of participants need to be considered individually, non-experts can provide both fresh impetus to disciplinary research and legitimisation in socio-technical contexts.

2 Methods

Transdisciplinary methods have been developed and applied to complex societal problems for more than two decades in urban planning, sustainable land use and other fields. There are two fundamentally distinct concepts of transdisciplinary research: Mode 1 transdisciplinarity describes the blurring of boundaries between disciplines in interdisciplinary research until they can no longer be distinguished from one another and the "original unity of science is restored" (Völker, 2004). Mode 2 transdisciplinarity, on the other hand, provides access to different thought styles and bodies of knowledge. In the following text, as in the TRANSENS project in general, the term "transdisciplinary" refers to mode 2 transdisciplinarity and follows the position of Pohl et al. (2017) by understanding mode 2 transidisciplinarity as the equal integration of practice actors and non-experts in an interdisciplinary research process aimed at solving a societal issue.

There are several taxonomies that allow distinction between different bodies of knowledge. TRANSENS most commonly uses the "three types of knowledge that science should provide to sustainable development" (ProClim, 1997): Systems knowledge, i.e., knowledge about the current situation; target knowledge, i.e., knowledge about the situation as it should be; and transformation knowledge, i.e., knowledge about the transition from the current situation to the target situation. Interactions are aimed at accessing and integrating the relevant types and bodies of knowledge.

1 The term "experts" is used here in the sense of "individuals with extensive system knowledge", which includes practice actors and scientists.

2 The term "citizen" is used specifically in the sense of "any member of the civil society without in-depth knowledge of NWM". Its use in this text can be considered equivalent to "non-expert" and appears only as part of the title of the Citizens' Working Group.

Depending on their intensity, four levels of interactions can be distinguished: Information; consultation, or mutual one-way information; collaboration, or co-production; and co-design, or joint decision-making (Pohl et al., 2017; Wiek, 2007). In the context of NWM, interactions at consultation level were commonly limited to the final project phase, took place within the national legal framework rather than within the scope of the project itself, and were mainly geared towards acceptance of project outcomes by (local) stakeholders (Martell and van Berendoncks, 2015). TRANSENS differs from other NWM research projects in two fundamental ways: Firstly, TRANSENS aims at higher levels of interaction, for example, by refining research questions together with non-experts and scientists[3], although the decision to include proposals in the research programme, and therefore the responsibility, remains with the scientists (Seidl et al., 2024). Secondly, the non-experts involved in the research are explicitly *not* stakeholders in the site selection process or NWM in general (Seidl et al., 2024; Röhlig et al., 2021; TRANSENS, 2019), while engineering and natural science topics form a significant part of their scope.

2.1 Planning of transdisciplinary workshops in research

Planning a workshop as part of transdisciplinary research requires the following steps: 1. Analyse (researcher) expectations; 2. Identify types of knowledge needed to meet those expectations; 3. Formulate specific research questions that can provide answers of the required type and level; 4. Select participants and suitable workshop methods (Ebeling et al., 2024a). At its core, this is a pragmatic selection from the Ten Steps approach aimed at scientists who want to - or need to - involve societal actors in their research (Pohl et al., 2017). This process is fundamentally different from many other applications of transdisciplinary workshops, where the participants with their types of knowledge emerge from the existing problem field, the questions or challenges are formulated together, and there are no specific expectations regarding the results.

2.1.1 Goals and expectations

Epistemic gain was not the goal of the workshops, nor is it a reasonable expectation for any transdisciplinary work, as Drögemüller and Seidl (2024) note. Scholz and Steiner (2015) distinguish four functions of transdisciplinary processes: Societal capacity building, consensus building, analytical mediation and legitimising by informal power. In engineering or scientific research, analytical mediation is the primary concern, and the two workshops discussed here dealt exclusively with analytical mediation. More specifically, they were aimed at evaluating and, if possible, improving established methods:

- *Method validation:* Are the presented paradigms, concepts and methods comprehensible? If invited to elaborate their own ideas, will participants without systems knowledge create and outline methods similar to those already established in the expert community?
- *Stress test:* If invited to critique the presented paradigms, concepts and methods, do participants identify any weaknesses that are currently not addressed? Which aspects and perspectives are of interest to the participants?
- *Technical impulse:* Are participants able to transfer their disciplinary knowledge to a new context and use this to provide input in terms of improving established methods?

As the planning phase progressed, the researchers' objectives became more refined so that their expectations were quite clear before the workshops commenced. However, the participants reported that the same was not true for them: Prior to the workshops, they were not able to form any specific expectations due to the brevity of the information given in the promotional materials. The aims and methods of the workshop remained quite unclear to them. In particular, the participants were not sure whether the main objective was to generate new knowledge or to educate the participants, i.e., their roles were not defined until the workshops started. When they signed up for the workshops, they merely expected to join a discussion group on an interesting but rather unfamiliar topic.

2.1.2 Types of knowledge

Previous TRANSENS workshops with a group of practice actors (Ebeling et al., 2024a) had led to the conclusion that the research required a format where participants were able to act as a "proxy" for individuals who had not previously interacted with the subject of nuclear waste disposal but were academically or otherwise highly educated in disciplines related to the NWM problem, such as geology, materials science, or others. The practice actors described such persons with extensive disciplinary knowledge but insufficient systems knowledge as "difficult stakeholders". An example of a dissent resulting from lack of systems knowledge can be found in Grambow and Ewing (2022). Based on the need to address potential arguments from "difficult stakeholders" as well as the objectives formulated above, it was decided that the prospective participants in the transdisciplinary process should have a high level of education in science and technology, but no system knowledge in the field of NWM.

2.1.3 Research questions

In the demonstration of repository safety, the concept of indicators plays a fundamental role. Indicators are parameters that signal certain conditions. Obtaining the information that certain conditions have been reached (or passed) allows for the indirect observation of complex processes or conditions that cannot be measured directly. Examples from other sciences can be used to illustrate the concept, e.g., in climate research: climate is a complex state, arrived at through superposition of many processes, and as such not directly measurable; whereas indicators such as precipitation, temperature and hurricane frequency each contribute to defining the climate. However, compared to this example, the terminology, time scale and processes relevant in

3 The term "scientist" is used in this text to refer to any individual who seeks to advance science, but in particular to those who do so in an academic setting (e.g., universities, research institutes). On the pitfalls of defining the participants in transdisciplinary research, see also Defila and Di Giulio (2018).

repository safety are much further removed from the everyday experience of the public. Consequently, it is more difficult to explain the use of indicators for assessing the long-term safety of repositories in a comprehensible manner to persons without prior knowledge: The challenge is to make terms such as "radioactivity flux from the geosphere to the biosphere" or "swelling pressure of the backfill" (to name but two examples for such indicators) more accessible, to convey a basic understanding of processes that are of relevance for their estimation, and to provide context to make the assessment period of a million years more relatable.

The two workshops discussed here were to address the question of which indicators are suitable for assessing repository safety and, at the same time, for communicating with the non-scientific public. Of particular interest was the use of graphs to communicate uncertainties.

2.1.4 Participants

The participants were recruited from among PhD students in the natural and engineering sciences at Clausthal University of Technology. The workshops were embedded in the postgraduate programme and were prominently advertised in a newsletter for doctoral students. Due to the recruitment from a very small pool of potential participants and the requirement to obtain model representatives for the "difficult stakeholders", the group was expected to be very homogeneous and not a representative sample of the German population. In the event, all six participants were male, of similar age and native German speakers. They represented the disciplines chemistry, geosciences, and engineering. The participants were united by a deep understanding of the scientific process and a trust in science and scientists that is not shared to this extent by the German population (Ziegler, 2022). The targeted selection in terms of thematic depth seems to suggest that the diversity of perspectives and thus thematic breadth is lost. However, it should be borne in mind that the "thematic breadth" to be covered refers to that of the subject matter experts involved in the safety assessment, and it is precisely their perspectives that are of interest for our research questions. The workshops were designed to complement a series of workshops on the same topics, which were conducted with a wider range of participants (including the Citizens' Working Group) and, consequently, with less disciplinary depth (Ebeling et al., 2024b; Ebeling et al., 2024a). The participants' high level of education notwithstanding, the workshops are examples of transdisciplinary work: Their lack of system knowledge, the broader context of the different workshop series and the specific requirements of the research question have to be taken into account.

2.1.5 Workshop methods

It became clear that co-design and co-production were difficult or even impossible goals to achieve within the given constraints, and interactions were designed from the outset at the level of consultation: Weekly intervals meant that topics, methods and materials for the entire workshop series had to be prepared beforehand, with little opportunity for participants to actively influence the process. In the first two workshops with the same group of participants (Ebeling et al., 2024b), different workshop methods had been tried out, and the plenary discussion proved to be a popular and fruitful method. For this reason, several methods considered during the planning phase of the third and fourth workshops, i.e., those discussed here, were discarded, as was a practical exercise on understanding scientific graphs. Instead, the technical work was carried out in plenary discussions. These were, however, preceded in several cases by a short pause for reflection or by short impulse presentations. As these changes to the schedule were not initiated by (or even discussed with) the participants, we do not consider these workshops to be co-designed.

The participants were given the following tasks:

1. Which indicator(s) would you use to demonstrate repository safety?
2. Which sources of uncertainties are conceivable, and which categorisation would you suggest for addressing uncertainties in the Safety Case?
3. How should information about uncertainties be communicated, and which digital tools would you use?
4. How can uncertainties be presented so that comprehensibility and complexity appear well balanced? Please draw drafts for graphics.

The questions were formulated at a rather abstract level. The participants were familiar with terms like "indicators" and "uncertainties" from their own everyday experience.

2.2 Implementation

The basic approach in conducting the workshops was to impart only absolutely necessary system knowledge on the subject of nuclear waste disposal in short introductions of approx. 10 min duration. This was to minimise influencing of the participants by the workshop organisers, e.g., through expression of opinion, the selection of teaching materials, etc. Participants should draw on their experiential knowledge as well as expertise from their respective disciplines to complete the tasks. They should be restricted as little as possible in their work, especially during the plenary discussions. For this reason, moderation of the discussions was exercised with great restraint. The aim of these measures was to reduce the potential for bias introduced by the workshop organisers.

At the start of the first workshop, the transdisciplinary approach was introduced and the expectations placed on all those present were clarified. All participants, moderators and observers were therefore clear about their roles: Participants would work on the tasks set by the moderators; moderators might intervene and guide the group if necessary; and observers were taking notes without interacting with either participants or moderators. Power asymmetry was not effective due to the particular actor constellation: With the exception of one senior observer, all persons involved were either participants in the PhD programme or were close to it due to their personal background and function in the scientific community; furthermore, with the exception of one observer, all persons involved had a natural sciences or engineering background. The aforementioned homogeneity therefore referred not only to the group of participants, but also included the majority of those conducting the workshops. Problems such as "confounded agendas" or "coexistent values" (Wiek, 2007), were circumvented. Rather, everyone involved, whether workshop participants or organisers, worked together as a team with common goals, albeit with different roles. This fundamental attitude is also reflected in the participants' self-assessment, in which objectivity and solution-orientation play a key role.

From the participants' perspective, the group's homogeneity was perceived as beneficial in a number of ways: A common technical vocabulary allowed for fast-paced discussions, and ideas could be quickly sketched out without having to explain the technical background at length. Discussions were characterised by an error culture that allowed for the admission of mistakes without any negative implications. In this environment, ideas could be expressed without fear of criticism and could serve as nuclei for in-depth consideration and development by the group. Here, the different professional specialisations and personal perspectives of the participants came into play, which they recognised as central to the development of the content. During plenary discussions, the participants did not run out of ideas or perspectives; on the contrary, the facilitators had to intervene several times in order to bring the discussion to a close. In retrospective, the participants viewed the good error culture and the appreciative behaviour in general as crucial for the success of transdisciplinary work, more so than in other collaborative work situations (e.g., research projects or laboratory work), as the transdisciplinary approach forced them to engage with ideas and topics that did not correspond to their own area of expertise and took them out of their comfort zone.

3 Results

The following analysis is based on the facilitators' and observers' notes, which contain a subjective, anecdotal selection of statements and results. They reflect the opinions and knowledge of the workshop participants. No audio recordings were made and there is no transcript of the discussions. As unclear or incorrect statements were repeatedly challenged by other participants, the absence of disagreement (verbal or non-verbal) was interpreted as agreement, i.e., statements made by one participant were taken to reflect the opinion of the whole group. Whenever unanimity is explicitly mentioned, all participants had signalled their agreement.

3.1 Communication and trust

The topic of knowledge transfer and science communication was of particular interest to the participants, since teaching and thesis supervision are often among the tasks of doctoral students and thus part of their everyday lives. The focus of the discussions was often not on the content to be communicated. Instead, other aspects of communication were more closely considered, with the intention of making communication more efficient. For example, work on the question "What indicators would you use to show the safety of the repository?" began with a comment about trust and perception, and other meta-level aspects such as context, level of complexity and level of detail were closely intertwined with the message content throughout the discussion. Participants agreed and accepted that in terms of effectiveness, there are limits to communication. The ultimate, if unattainable, goal would be to make the sender's and receiver's messages congruent ("they hear what I say").

Regarding the recipient, the general public, there are two major challenges: technical expertise and trust in the senders. Some tasks were therefore implicitly addressed at two levels:

- Under which conditions will the message be perceived by the recipients in the first place and then considered worth dealing with?
- How must the content be selected and prepared so that the interested public can understand the information and draw valid conclusions?

The participants did not elaborate on the issue of trust, but it was implied in all discussions that trust in science as such, trust in scientists as fallible human beings, and/or trust in the site selection process is lacking amongst members of the general public. The possibility of instrumentalising information was illustrated with the example of monitoring: "Why are you measuring this? Are you not sure [of your design's reliability]?" Instead of promoting a sense of safety through regular measurements, clever framing could turn the message into the opposite and promote mistrust and anxiety.

Target group-oriented communication was viewed sceptically: "Target group-oriented communication means that everyone else falls by the wayside". On the other hand, the necessity was seen: "You cannot please everyone". The group was also divided on the issue of data availability: On the one hand, open access to all data was seen as a necessary prerequisite for transparency and meaningful participation; on the other hand, there was concern that de-contextualised information could be misunderstood or misused.

An interesting question that arose from the discussion on uncertainties was formulated as follows: "Are people supposed to actively seek information or are they "bombarded" like during a commercial break on TV"? The discussion on motivation was not pursued further, but was touched upon several times in relation to entertainment, e.g., in the context of superhero comics, which participants believed to have promoted acceptance of nuclear energy production in the 1950s and 1960s. The suggestions of talk shows and satirical programmes as potential means of communication also point to passive reception of information through entertainment.

3.2 Indicators as a communication tool

3.2.1 Contextualisation of indicators

The participants first looked at communication in general - the discussion on target group-oriented communication described above also took place within the scope of this task - and at contextualisation in particular.

Communication should provide spatial and temporal context to make it more relatable: Where is surface contamination unlikely, possible, or almost certain? What will happen in the next decades, generations, or centuries? As one participant stated: "I care about the next 1,000 years. I do not care who owns my property after that". Other examples of contextualisation were given: Reference values and limits - how are they determined? Trustworthiness - who collected the data and made the calculations? A brief discussion arose about how views and evaluations of indicators can vary over time and depending on the social context. This stretched the arc even further and embedded the use of indicators in the overall context of society and science. Participants gave two examples: One possibility is that new knowledge will give the indicator a new significance "like the atmospheric CO_2 concentration, after its role in the greenhouse effect was better understood". Another possibility is that society's values and (risk) perceptions may change over time: "the cloning of non-human mammals is becoming more acceptable".

3.2.2 Indicator properties

Participants identified a number of properties that a suitable indicator should possess:

- *Relevance:* The indicator has to be effective and specific ("the indicator must represent what we want to represent").
- *Communicability:* The statements made by the indicator must be easy to convey. This also includes comparability with experiences from personal everyday life. In order to address a range of target groups effectively, the use of several different indicators should be considered.
- *Uncertainties* must be taken into account and communicated. Since they increase in both space and time, the indicators "must be adjusted for time", i.e., selected for their suitability in regard to the time frame under assessment.
- *Measureability:* Participants mentioned (environmental) monitoring several times, implying that measurability is a desirable characteristic.
- *Practicability:* This characteristic was mentioned, but not elaborated. In this context, the term can mean that the derivation of the indicator should not be too complicated or computationally time-consuming.

3.2.3 Indicator type

Workshop participants often expressed repository safety in terms of a probability without specifying the event in question (although two possible interpretations were given as "something goes wrong" and "I get cancer"). However, the concept of "risk" was not considered very suitable for public communication purposes, since statistical relationships were deemed difficult to convey. This is particularly relevant here because several interrelated probabilistic processes had to be considered (probability of exposure; probability of developing cancer after exposure).

Several indicators already established in the expert community were discussed, including material flux, permeability, mechanical stability, dose, surface radionuclide concentration, cancer risk, and radiation exposure risk. Participants offered suggestions for indicators not currently established that might be useful in communicating with the public:

- *Impact:* The indicator either directly quantifies the impact of the repository at the surface or allows for an estimate of this impact. This was not further elaborated, e.g., how "impact" is defined and how it should be quantified. However, during the discussion of another task, it was suggested that the area affected by exposure should be estimated.
- *Receptivity:* Under the premise that "there is no repository safety without acceptance of the population" (P. Hocke, verbal communication), this parameter describes the population affected by the site selection process. It should capture "the population's willingness to receive information" and take into account "how information is transported, processed and (mis) understood". It therefore includes information literacy (the ability to understand information), but additionally also considers the recipient's attitude and openness of thought (their willingness to engage with the information). The proposed parameter is closely related to the concept of information receptivity (Brock and Balloun, 1967; Manika et al., 2021).

The basic approach proposed by the group was to prepare and make available all indicators that are suitable in principle, but to select only a few for communication in the mass media. However, the group did not specify which indicators or types of indicators they considered most appropriate for this task.

3.3 Categorisation of uncertainties

In task 2, participants were asked to reflect on possible categorisations of uncertainties with the intention of comparing their results and motivation with the established method. The first step was to compile sources of uncertainty. The top entry in the list was "time", followed by factors that change over time, such as the evolution of society and the political framework. One idea that had already occupied the group in connection with the formal site selection procedure was that new findings or changed social values might lead to a re-evaluation of facts (see 3.2.1). Other sources referred to modelling in the broadest sense, e.g., assumptions, parameter variability and numerical effects. Humans as a source of error were mentioned, as was the availability and comprehensibility of the documentation produced. Climate, environment and economy were named as further sources of uncertainties.

Despite the previous discussion on the instrumentalisation of information (see above), participants agreed that uncertainties needed to be disclosed as an integral part of all communications. Different categorisations of uncertainties were explored. Without explicitly mentioning it, different dimensions of uncertainties were considered: their cause, impact and treatment.

Among the suggestions for categorisations, several pairs of opposites were mentioned, such as "controllable - not controllable" and "predictable - not predictable". Two further suggestions had three categories or levels, "human - time - data" and "not relevant - relevant - leads to termination of the project". The only proposal with a larger number of categories was the idea of categorising uncertainties according to the discipline responsible for their respective reduction. Variability of rock properties would thus be assigned to geology, whereas variability of container materials would be assigned to materials science. Participants remained dissatisfied with the proposed classifications, as they either fell short, categories overlapped, or other issues became apparent. The use of multiple categorisations in parallel according to different criteria was therefore considered. Without naming a specific result, the use of a two-dimensional hierarchical categorisation including the potential for treatment was favoured.

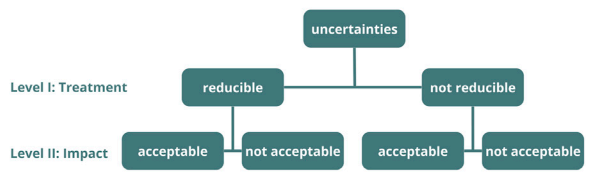

FIGURE 1
Example for proposed categorisation of uncertainties. Level 1: treatment of uncertainties, level 2: impact of uncertainties.

The categorisation in Figure 1 was an example given during the workshop, and contains two of the four dimensions proposed by Eckhardt (2021) for the evaluation of uncertainties in the Safety Case.

The question of a motivation for such a categorisation was not raised by the group; it was only mentioned in an aside that the categorisation of uncertainties "influences how we deal with them", without this point being taken up further in the discussion. The discussion on the topic of uncertainties nevertheless focused on a related question: Does the decision for a certain categorisation of uncertainties change the safety evaluation of the repository? Acknowledging this led to a further question: Does the categorisation influence future actions? Once again, the group of participants was unanimous in coming to a positive answer. The main line of reasoning was that the prioritisation of the categorisations has an influence on the subsequent treatment of the problem; in this respect, the categorisations are important for future outcomes and may therefore trigger different responses.

3.4 Communication of uncertainties

In task 3, participants' attention was deliberately drawn to digital formats in order to ensure that they would consider the additional tools and opportunities offered by digitalisation. While the researchers intended this to refer to the use of digital tools within the formal framework of the Safety Case, the participants interpreted the question much more broadly. In line with the general approach to workshop facilitation, the group was allowed to pursue its discussion. Consequently, the use of a whole range of different formats for different conditions and purposes was discussed. Examples are educational videos for school lessons; webinars and Q&A sessions with experts for the interested public; podcasts, talk shows and documentaries on streaming platforms as easily accessible information sources; graphic novels and educational game apps for playful learning of younger people.

Participants identified the following challenges for successful communication of uncertainties:

- *Adaptation to the needs of many different target groups:* Level of detail, wording and format must be tailored to the audience and their (presumed) background knowledge. The need for granular adaptation was expressed by one participant's comment that "15-year-olds communicate differently than 25-year-olds", referring to the preferred social media platforms of different age groups.
- *Trustworthiness of the format:* TV documentaries were perceived as more valuable than videos on internet platforms; print media in turn as more trustworthy than TV. There are personal preferences for information channels and the use of a few conventional formats may fail to reach a significant portion of the population.
- *Short attention span:* Intensive engagement with a complex topic like NWM requires time and concentration. This was seen as problematic in a time when an endless number of short messages and videos compete for attention.
- *Timeframe:* The process, which spans several generations, must counteract problems such as loss of knowledge and disinterest. The same questions will be asked many times by the public.

The participants identified various instruments that support communication:

- *Interactivity:* The user's ability to control the level of detail was judged to be of particular importance.
- *New technologies:* The use of virtual reality and artificial intelligence offers new possibilities. AI could be used, for example, to answer questions in an internet forum created for this purpose.
- *Didactic methods:* The importance of graphics was emphasised ("a picture is worth a thousand words") and various stylistic devices were mentioned, including humour and satire.
- *Contextualisation:* Uncertainties should be "embedded in the whole package", as their relevance only becomes apparent in the context of the specific topic. This includes an appraisal of their impact - or lack of impact - on the safety of the repository.
- *Framing:* Embedding in a narrative involves a selection and evaluation of information and often has negative connotations ("the evil atom"). However, suitable framing can also have a mobilising effect: "I would rather click on the page "safety-in-the-repository.de" than on "uncertainty-in-the-repository.de".

In task 4, participants created sketches of graphs showing data with uncertainties. One of these proposals is presented in Figure 2 as an example.

Starting with Monte Carlo simulations for multiple scenarios (Figure 2A), the maximum values for each scenario and each time point (i.e., the upper envelope) should be plotted on a single graph (Figure 2B). Adding the limit or reference value to the plot allows identification of "problematic" scenarios that require further work. If a continuous parameter is varied between scenarios, a 3D surface could be interpolated (Figure 2C). If minimum values are also of interest, they could be used to create a 3D surface that encompasses all values resulting from the considered scenarios. Color can be used to encode the probability of values occurring. Other tools such as contours, interactivity (rotation, zoom) can be added. The participants further discussed the possibility of creating a dimensionless parameter in order to characterize the uncertainties in each scenario.

Another participant suggested plotting the curve of maximum doses from all calculated scenarios in an X-Y scatterplot. The

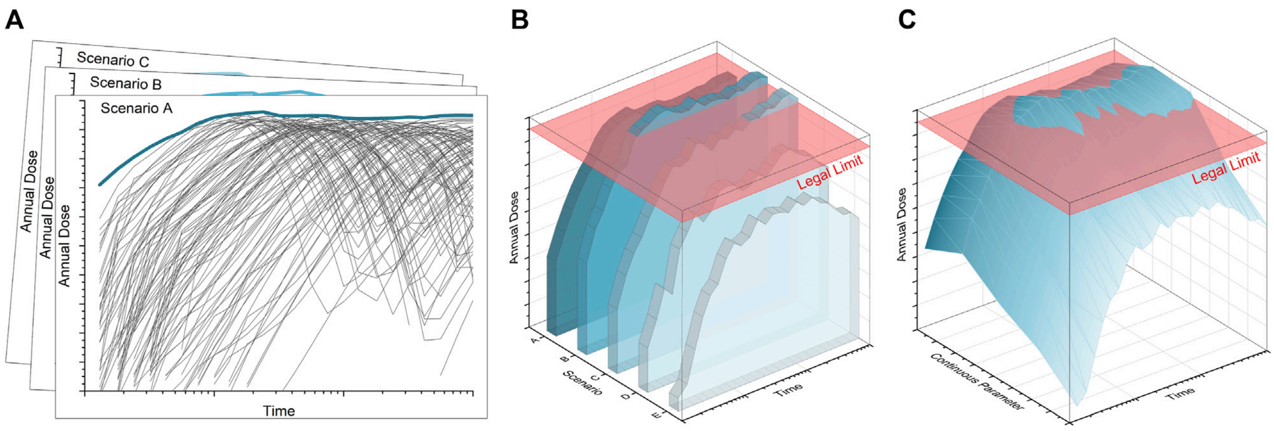

FIGURE 2
Participants' suggestions for the visualisation of Monte Carlo simulations. **(A)** Individual runs with upper envelope, **(B)** area below maximum for five discrete scenarios; **(C)** maximum plane as interpolation of several scenarios differentiated by a continuous parameter.

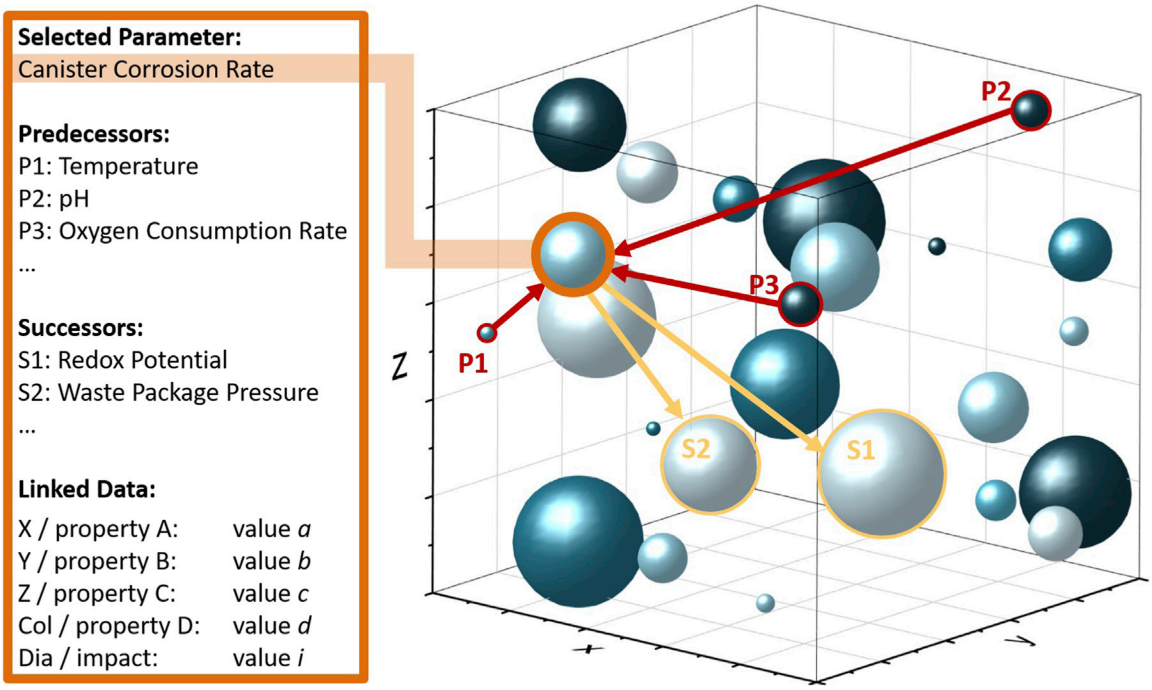

FIGURE 3
Interactive 3D network diagram suggested by workshop participants. Each marker represents an uncertainty. Clicking on a marker highlights the uncertainties' predecessors (P1 - P3) and successors (S1, S2) and opens a context menu with information regarding the selected uncertainty.

presentation is to be in the style of an infographic. Features are to include the use of "yellow barrels" as markers; icons for "a playing family" and "a hazmat suit" to indicate the safe and hazardous dose value ranges, respectively; and the marking of limit and reference values. Such an infographic is to be created for each time of interest.

A third suggestion concerned an interactive network diagram (Figure 3). Each bubble represents one uncertainty. Including color and size, it is possible to encode continuous or categorical data in five dimensions. Clicking on an uncertainty reveals information about it, while clicking on the link between two uncertainties reveals information about the relationship between them. Participants suggested the use of shading, cross-hatching or colour saturation to add a further dimension to the graphs (e.g., a graduated colour band representing probability from 0 to 1), but showed awareness of both the emotional and evaluative effect of colours and potential accessibility issues.

4 Discussion

The results below were selected to provide examples for the application of transdisciplinary methods for method

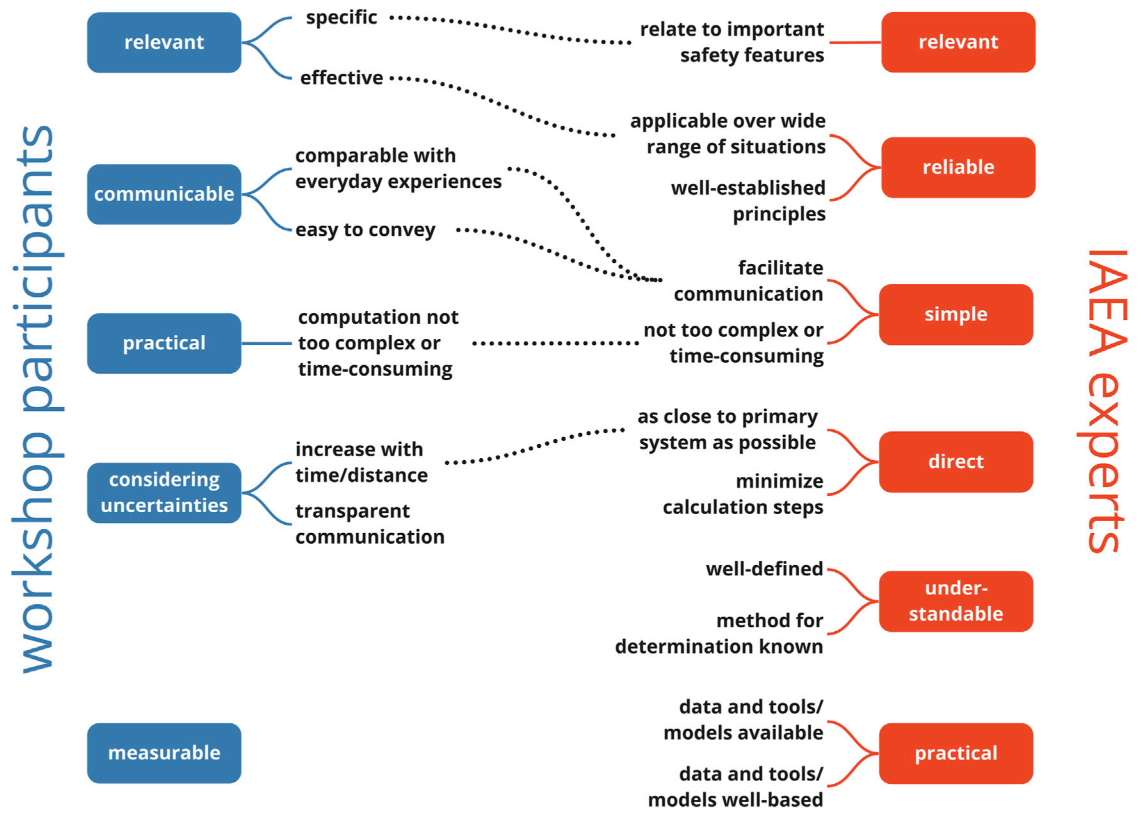

FIGURE 4
Comparison of indicator properties collected by workshop participants and by IAEA experts. Illustration based on data taken from International Atomic Energy Agency (1994).

validation, method optimisation and generation of technical impulses.

4.1 Indicator properties

Task 1 asked participants to list important indicator properties, inviting them to "reinvent the wheel" in order to check whether a set of established criteria was inherently plausible and complete. The discussion of this particular task was chosen to illustrate the effectiveness of the transdisciplinary approach for method validation purposes. Figure 4 shows a comparison of the participants' results as presented in section 3.2.2 with the "desirable characteristics of safety indicators" listed by the International Atomic Energy Agency (1994). It shows that many of the concepts compiled by the IAEA experts were either explicitly addressed or implied by the workshop participants. Notable exception are properties related to the determination of the indicator value. It was apparent from the discussion that they assumed that this would be unproblematic and relevant methods well-established. Noteworthy is the additional criterion of measurability. The participants repeatedly implied that the indicator should be measurable. This, in turn, implies that the indicator (or the parameter it is directly derived from) is detectable at the Earth's surface or at least close to the surface, e.g., in groundwater or soil. It is conceivable that measurability may be even more important for the general public, who are less familiar with modelling and less trusting of scientists. Whether measurability is technically relevant or useful is besides the point: The decisive factor is that a value perceived as "real" or "true" is available, which can be compared with previous model calculations if necessary.

4.2 Visualisation of uncertainties: 3D interactive network diagram

Task 4 (see section 3.4) asked participants to prepare sketches of graphs that might help to communicate uncertainties. The discussion of this task was chosen to illustrate the potential adaptation of an existing method for an additional purpose. One of the suggestions made by the workshop participants was the creation of an interactive network diagram as shown in Figure 3. All uncertainties related to the evaluation of repository safety could be represented in a 3D diagram. Including colour and marker diameter, five categories would be available to encode relevant data, with marker diameter an intuitive choice to represent the impact of the uncertainty on the end result. Predecessor-successor relationships could be easily visualised. The data stored for each uncertainty could be displayed in pop-up windows or tooltips. Although network diagrams are in use for tracking parameter relationships and/or uncertainties, e.g., as part of the database maintained by the German implementer, Bundesgesellschaft für Endlagerung mbH, these are designed to facilitate the preparation and review of the Safety Case by experts. They are not suitable for use by non-experts, or to communicate with the general public. However, it should be feasible to extract the relevant information and build an interactive diagram as envisaged by the workshop participants, with one caveat: In order for the size of the bubbles to be a meaningful representation of safety relevance, there must be a method of assessing the impact of uncertainties that is common to all parameters.

4.3 Communication of uncertainties: Dimensionless parameter

Task 3 (see section 3.4) asked participants to reflect on the communication of uncertainties. The discussion of this task was chosen to demonstrate the potential for disciplinary impulses. Starting with graphs showing the results of Monte Carlo simulations, the participants discussed the use of the Buckingham Pi theorem to create a dimensionless parameter that would allow the comparison of the uncertainties of different scenarios. The basic requirement for comparability is that the diagrams share a common structure. If the uncertainties contained in each diagram could then be expressed as a single numerical value, the uncertainties of a large number of simulations would be easily comparable. Potentially, the information content of many complex diagrams could be condensed into a simple bar chart, and would then be easy to convey in public communication. Although the underlying methods and assumptions may be too complex for non-experts to understand, they could be used to effectively illustrate site comparisons, different design concepts and alternative evolutions of the repository. This line of thought, not elaborated further during the workshops due to time constraints, may serve as an example of disciplinary inspiration by persons without systems knowledge.

4.4 Conclusion

The participants did not offer any preferences regarding the choice of indicator(s) for the safety assessment. However, they favoured indicators that were directly measurable and could be used to estimate the impact on the surface caused by a loss of containment. The immediate future, 1,000 years at most, was of particular importance. Uncertainties should be communicated transparently. Communication with the general public should make use of interactive graphics: The user should be able to adjust the level of complexity and information content as required.

Similarities in the backgrounds of the participants helped to deepen the discussions. A greater diversity of perspectives can be achieved by other means, e.g., by including participants from different organisations or personal backgrounds. Careful selection of research questions that focus on the interface between science and society, or on a social or societal aspect of the research topic, offers the best chance of producing useful results in science and engineering research.

Transdisciplinary research is resource intensive in the planning and implementation phases. Experiments cannot be repeated and results are not amenable to statistical processing. Transfer, e.g., of methods, to other groups or contexts is limited. For each project, a thorough analysis has to indicate whether a transdisciplinary approach is appropriate for the problem at hand. In the case of NWM, research is addressing a complex, costly problem with an extremely long time horizon that affects the entire population. The choice of a transdisciplinary approach therefore seemed appropriate and our results confirm this: The content developed by the participants during the workshops was similar to the findings of experts. This supports the plausibility and comprehensibility of the contents and methods under consideration and thus strengthens their legitimacy. The transdisciplinary approach has been shown to be effective in scientific and engineering research for the purposes of method validation, stress testing and technical impulse generation.

For future applications of the transdisciplinary approach in natural scientific or engineering research, the theoretical basis and terminology need to be refined and a toolbox of methods should be developed specifically for these applications. On the basis of the ten-step approach Pohl et al. (2017), specific guiding questions could be formulated to help assess the suitability of research questions for transdisciplinary treatment and to support the planning phases of transdisciplinary workshops.

Data availability statement

The datasets presented in this article are not readily available because the data contains information which allows the identification of individuals. Requests to access the datasets should be directed to martina.heiermann@tu-clausthal.de.

Ethics statement

Ethical approval was not required for the studies involving humans because the research is based on workshops offered within the framework of a postgraduate programme, i.e., within an established educational setting. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MH: Investigation, Writing–original draft. VO: Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Brock, T. C., and Balloun, J. L. (1967). Behavioral receptivity to dissonant information. *J. personality Soc. Psychol.* 6, 413–428. doi:10.1037/h0021225

Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit (2020). *Verordnung über Sicherheitsanforderungen an die Endlagerung hochradioaktiver Abfälle: EndlSiAnfV*.

Bundesministerium für Umwelt Naturschutz und nukleare Sicherheit (2022). *Verordnung über Anforderungen an die Durchführung der vorläufigen Sicherheitsuntersuchungen im Standortauswahlverfahren für die Endlagerung hochradioaktiver Abfälle: EndlSiUntV*.

R. Defila and A. Di Giulio (2018). *Transdisziplinär und transformativ forschen: Eine Methodensammlung* (Wiesbaden: Springer VS).

Deutscher Bundestag (2017). *Gesetz zur Suche und Auswahl eines Standortes für ein Endlager für hochradioaktive Abfälle: StandAG*.

Drögemüller, C., and Seidl, R. (2024). "Die Arbeitsgruppe Bevölkerung im Projekt TRANSENS," in *Transdisziplinäre Ansätze in der nuklearen Entsorgungsforschung: Erfahrungen und Reflexionen aus dem Projekt TRANSENS* (TRANSENS-Bericht Nr. 17). doi:10.21268/20240529-2

Ebeling, M., Heiermann, M., and Müller, J. (2024a). "Planung und Durchführung transdisziplinärer Workshops zur Optimierung des Safety Case," in *Transdisziplinäre Ansätze in der nuklearen Entsorgungsforschung: Erfahrungen und Reflexionen aus dem Projekt TRANSENS* (TRANSENS-Bericht Nr. 17). doi:10.21268/20240529-3

Ebeling, M., Heiermann, M., and Röhlig, K.-J. (2024b). *Opportunities for the further development of the safety case for deep geological repositories by transdisciplinary research – FEP catalogs and scenario development*.

Eckhardt, A. (2021). *Sicherheit angesichts von Ungewissheit. Ungewissheiten im Safety Case*. Zollikerberg: TRANSENS-Bericht Nr. 01. doi:10.21268/20210412-0

Grambow, B., and Ewing, R. C. (2022). "Safety, science and system analysis," in 3rd conference on key topics in deep geological disposal, Cologne (Deutsche Arbeitsgemeinschaft Endlagerforschung).

International Atomic Energy Agency (1994). *Safety indicators in different time frames for the safety assessment of underground radioactive waste repositories: INWAC subgroup on principles and criteria first report of the for radioactive waste disposal*.

International Atomic Energy Agency (2012). *The safety case and safety assessment for the disposal of radioactive waste*.

Manika, D., Papagiannidis, S., Bourlakis, M., and Clarke, R. M. (2021). Drawing on subjective knowledge and information receptivity to examine an environmental sustainability policy: insights from the UK's bag charge policy. *Eur. Manag. Rev.* 18, 249–262. doi:10.1111/emre.12453

Martell, M., and van Berendoncks, K. (2015). Integrating societal concerns into research and development (R&D) on geological disposal at the national level. *Mineral. Mag.* 79, 1563–1571. doi:10.1180/minmag.2015.079.6.31

Pohl, C., Krütli, P., and Stauffacher, M. (2017). Ten reflective steps for rendering research societally relevant. *GAIA - Ecol. Perspect. Sci. Soc.* 26, 43–51. doi:10.14512/gaia.26.1.10

ProClim (1997). *Research on sustainability and global change—visions in science policy by swiss researchers*.

Radioactive Waste Management Committee (2013). *The nature and purpose of the post-closure safety cases for geological repositories, safety case brochure 2012*.

Röhlig, K.-J., Ebeling, M., Eckhardt, A., Hocke, P., and Krütli, P. (2021). Transdisciplinary research on repository safety: challenges and opportunities. *Saf. Nucl. Waste Dispos.* 1, 205–207. doi:10.5194/sand-1-205-2021

Scholz, R. W., and Steiner, G. (2015). The real type and ideal type of transdisciplinary processes: part I—theoretical foundations. *Sustain. Sci.* 10, 527–544. doi:10.1007/s11625-015-0326-4

Seidl, R., Drögemüller, C., Krütli, P., and Walther, C. (2024). *Die Arbeitsgruppe Bevölkerung (AGBe) in TRANSENS: Bestimmung und Rekrutierung*. Hannover: TU Clausthal. TRANSENS-Bericht Nr. 15. doi:10.21268/20240219-1

TRANSENS (2019). *Forschung zur Verbesserung von Qualität und Robustheit der soziotechnischen Gestaltung des Entsorgungspfades: Vorhabenbeschreibung*.

TRANSENS-SAFE (2023). *Optimierung des Safety Case durch transdisziplinäre Forschung: Ergebnisse der Selbstevaluierung im transdisziplinären Arbeitspaket SAFE*. doi:10.21268/20230605-3

Völker, H. (2004). "Von der Interdisziplinarität zur Transdisziplinarität?," in *Transdisziplinarität. Bestandsaufnahme und Perspektiven*. Editors F. Brand, F. Schaller, and H. Völker (Göttingen: Universitätsverlag Göttingen), 9–28.

Wiek, A. (2007). Challenges of transdisciplinary research as interactive knowledge generation: experiences from transdisciplinary case study research. *GAIA - Ecol. Perspect. Sci. Soc.* 16, 52–57. doi:10.14512/gaia.16.1.14

Ziegler, R. (2022). *Zum Wissenschaftsvertrauen in Deutschland: Erkenntnisse aus dem Wissenschaftssurvey Wissenschaftsbarometer*.