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Opportunities for the further development of the Safety Case for deep geological repositories by transdisciplinary research – FEP catalogs and scenario development

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In the TRANSENS research project (2019–2025), large-scale transdisciplinary research on nuclear waste management is being conducted for the first time in Germany. Transdisciplinary in this context means that non-specialists and practice actors are systematically involved in developing and addressing research questions. One out of four TRANSENS research topics is addressing optimization potential for the Safety Case (SC) for Deep Geological Repositories (DGR) for nuclear waste. Seven workshops on this topic were held with three working groups, which differed from one another in terms of their types of knowledge. The work focused on the area of FEP (features, events, and processes) and scenarios. It also shows how objections and optimization proposals for safety cases differ between the various transdisciplinary working groups. Accessibility of SC content was identified as a fundamental area for improvement. Summaries of the report that are appropriate for various target audiences were called for, as was the inclusion of experts from outside the established SC community. The use of digital presentations and communication options was examined in detail. Regarding FEP processing, matrix forms of representation were discussed which, in addition to representing general dependencies, can also depict the strength of these dependencies. There were also proposals for the use of a morphological box to achieve this goal and to be able to create scenarios from FEP. Suggestions were made as to when FEP should be excluded from catalogs, when scenarios can be discarded and how these processes could be documented. To find previously unknown FEP, ideas were put forward regarding a reward system through which the general public could contribute to the completeness of the FEP catalog. In all workshops, promising and valuable results (e.g., criticisms, ideas) were achieved through transdisciplinary research. In TRANSENS, it was proven that the participation of non-experts in research can lead to substantive and in-depth suggestions for improvement. This also means that meaningful contributions based on participatory research are possible in broad participatory processes such as the German site selection procedure. It remains to be seen to what extent the results obtained in TRANSENS will be considered in the preparation of the future German Safety Cases.

KEYWORDS

transdisciplinary research, Safety Case, nuclear safety, FEP, scenario development, TRANSENS, deep geological repository, nuclear waste management

1 Introduction

How can safety be demonstrated? Citizens and authorities expect this question to be answered for repositories of radioactive waste and spent nuclear fuel. Compared to many technical applications that require classical proof of safety, the disposal of nuclear waste poses a particular challenge. This is due to the long period of time for which the isolation and containment performance of the repository system must be shown in different countries. The state-of-the-art method to address this challenge is known as the "Safety Case". In the context of nuclear waste disposal, this describes a collection of *scientific, technical, administrative and managerial arguments and evidence* which support the safety of the entire disposal system (IAEA, 2012). Both operational safety and long-term safety are relevant for repository systems. Scenarios play a particularly important role in the assessment of long-term safety. These scenarios describe the possible future evolutions (i.e., for the entirety of the repository system) and form the basis and framework of the simulations utilized in long-term safety assessment. Requirements for safety assessment and the role and methodology of scenarios are described in detail in (NEA/RWM/R, 2013).

Scenario development in German safety analyses follows an approach in which the FEPs (features, events and processes) are compiled in a catalog that indicates the mutual influences. This information forms the basis for a subsequent systematized combination of FEPs into scenarios. In safety assessment, this combines basic information such as site description and inventory with repository concept and system analysis (Lommerzheim et al., 2019). In Germany, the consideration of future evolutions is part of the legal regulations. The required containment of the waste must be demonstrated over a period of one million years (assessment period) (StandAG, 2017). During this period, scenarios for both expected and deviating evolutions must be systematically considered (EndlSiAnfV, 2020). FEP-based scenario development is therefore of great importance in the German site selection procedure.

In the TRANSENS research project (2019–2025), large-scale transdisciplinary application-oriented basic research on nuclear waste disposal is being carried out for the first time in Germany. This kind of research is based on an approach which means that non-specialists are specifically involved in research activities on an equal footing. The great need for targeted communication of technically complex interrelationships in the field of nuclear waste management is already described in OECD/NEA (2017). TRANSENS is developing from this on further approaches.

One field of research in TRANSENS focuses on ways to optimize the Safety Case (Transens, 2019). Röhlig et al. (2022) describe that the Safety Case goes beyond a technical tool and its content must therefore be seen in a societal context. The area of safety would affect all stakeholders and interested groups, as well as non-specialists. Therefore, the basic ideas and benefits of a Safety Case must also be comprehensible for these groups. The authors describe the possibility of solving this problem through transdisciplinary research resp. exchange.

This article presents results that were generated in particular regarding the topic of FEP and scenario development. The basis for the scientific work was the transdisciplinary and intensive collaboration with three different working groups, which is described in detail in Ebeling et al. (2024). Another research focus was transdisciplinary work on the topics of uncertainties and indicators. The implementation and results of these workshops are presented in the corresponding article by Heiermann and Olszok (2024).

2 Transdisciplinary workshops and methods

Safety Cases are an established basis for decision-making in various international repository projects. However, approaches, standards and procedures are also critically scrutinized. One aim of TRANSENS is to use transdisciplinary research to find out where optimizations are possible or necessary and what these could look like.

The exact understanding of transdisciplinarity is not uniform in science (Klein, 2017; Maasen, 2010). The various concepts range from particularly intensive interdisciplinarity to a combination of interdisciplinarity and work with actors from outside academia. The definition of transdisciplinarity pursued in TRANSENS goes beyond pure interdisciplinarity. Non-scientific actors are understood as an "extended peer community" in the sense of (Funtowicz and Ravetz, 2003). In this context, "non-scientific" is defined as a predominant lack of systems knowledge (cf. ProClim, 1997) on nuclear waste management. However, the focus group as practice actors did have systems knowledge.

The following questions should be clarified by working with groups that differ in terms of their knowledge types:

- Which elements of a Safety Case are understood and, above all, which are viewed critically?
- How the communicative accessibility of the safety case can be improved?
- Which alternative suggestions (here FEP and scenarios) are made by the groups?

2.1 Working groups and types of knowledge

All interactions during the following studies were supervised by members of the TRANSENS team. Team members were characterized by a high level of knowledge in the field of the Safety Case (system knowledge). The three working groups with which transdisciplinary

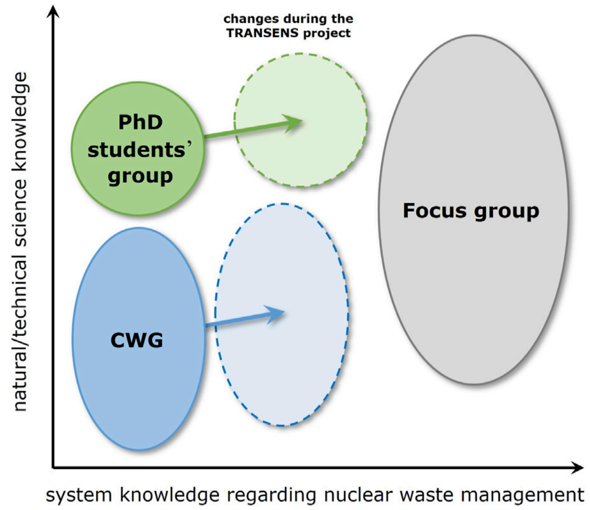

FIGURE 1
Schematic illustration of the knowledge base of the three working groups. CWG: Citizens' workgroup (translated from Ebeling et al., 2024).

work was carried out are referred to below as "Focus group," Citizens' workgroup (CWG) and "PhD students' group." The Focus group was a group of ten participants recruited at the beginning of the project. It consisted of experts who already had had professional experience with Safety Cases, i.e., who had system knowledge. This included individuals concerned with SC content creation such as conceptualization, scenario development or modeling, individuals reviewing Safety Cases as well as individuals involved in knowledge transfer, e.g., in order to enable informed participation of the general public. The knowledge backgrounds of the participants therefore ranged from science and technology to social sciences. All members were officially invited in advance by the TRANSENS team. They were advised not to act as representatives of organizations but as individuals with individual views and experiences. To allow and encourage this, the format was carried out obeying the so-called Chatham House Rule, in brief: "*When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.*" (cf: https://www.chathamhouse.org/about-us/chatham-house-rule). The CWG, on the other hand, consisted of 17 citizens who were recruited for the research project based on an online survey and an ensuing multi-stage and criteria-based procedure (Seidl et al., 2024). At the start of the project, none of the group members had any system knowledge relating to the final disposal of nuclear waste.

As it turned out, a certain type of knowledge was not covered in these formats, albeit it, according to the experience of the Focus group participants, plays an important role in the discourse about nuclear waste management: a combination of a higher level of scientific knowledge in disciplines relevant for the issue with little system knowledge. Following an invitation from the *Graduate Academy* of *Clausthal University of Technology*, a working group of six PhD students was formed. Like the CWG, care was taken to ensure that no one had any prior knowledge of nuclear waste management systems.

Figure 1 schematically shows the differences between all three groups regarding the types of knowledge relevant to the research work. The content-related project work led to a continuous increase in system knowledge in the CWG and the PhD students' group.

2.2 Implementation of the transdisciplinary workshops

Two full-day workshops were conducted with the Focus group (cf. Figure 3). As the name suggests, these were focus group experiments (cf. Morgan, 1996). A moderator from the TRANSENS research team asked the group key questions about the Safety Case in general. The answers and the reactions of the participants were recorded by passive observers.

As the CWG had almost no system knowledge, a workshop was held at the start of the collaboration with the aim of sharing knowledge in the field of nuclear waste disposal and the Safety Case. After the first workshop, a topic for further elaboration was selected by the group as part of a transdisciplinary co-design. The topic selected by the CWG was FEP. This was followed by a full-day workshop, for which the CWG was sent preparatory material in advance. The aim of the workshop was to validate established methods based on FEP and to optimize them. Following a short presentation, tasks were carried out in small groups using a FEP catalog (selection). The goal was to work out mutual influences between FEP and develop suitable processing methods. Questions were asked as to whether FEP were missing and whether weaknesses in the method had been discovered. In a further co-designed process, the CWG decided to hold another meeting on the topic of scenario development. Two keynote presentations on scenario development and repository system evolution were given during this third CWG workshop. Participants then worked in two small groups on the topic of "deviating evolutions." A further exercise took place in plenary on the topic of scenarios for deviating evolutions and their consequences.

Four workshops were held with the PhD students' group in TRANSENS. This article deals with the first two meetings, which focused on the Safety Case in general and FEP-based scenario development. The third and fourth workshops are described in the corresponding article by Heiermann and Olszok (2024). In contrast to the workshops with the CWG, the presentation of established methodologies by the research team did not take place at the beginning, but after the exercises, so as not to influence the participants in advance. The participants were given the task of independently developing a procedure to demonstrate the safety of a nuclear repository. They then had to explain and justify their concept to the TRANSENS team. The approach of a scenario development via FEP was presented and discussed with them in a Silent Discussion (cf. Will, 2016). Figure 2 compares all working groups and the respective workshops.

3 Results of the transdisciplinary workshops

This chapter focuses on the results of all seven workshops (i.e., two with the Focus group, three with the CWG and two

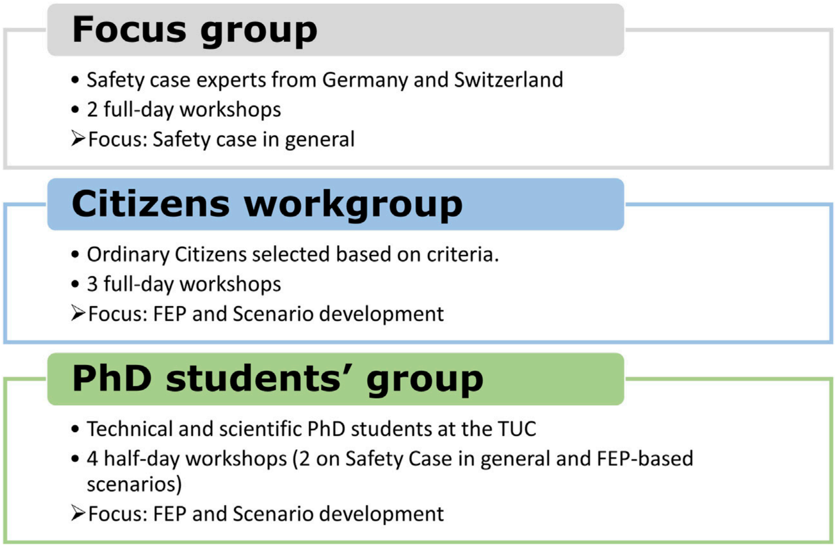

FIGURE 2
Overview of the working groups and workshops reported in this paper. TUC: Clausthal University of Technology.

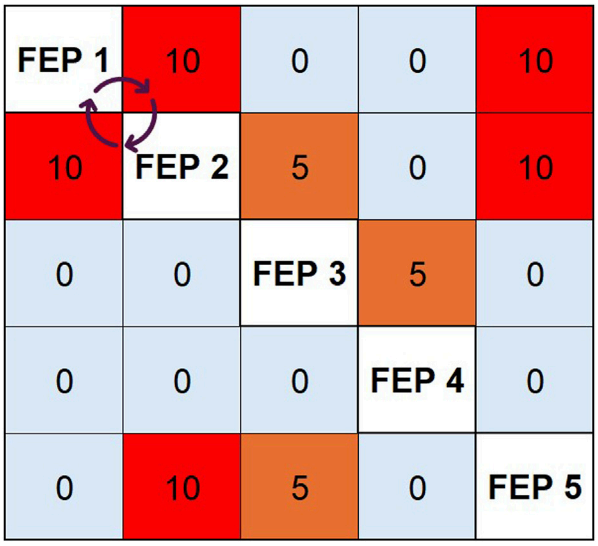

FIGURE 3
FEP matrix based on a CWG proposal. Color and numbers represent the strength of the influences. Reading is clockwise. Similar concepts have already been presented by Bailey and Billington (1998) but were not known to the CWG.

with the PhD students' group). Results are understood here as contributions, ideas and criticisms from the three working groups. In this article the focus is on the fundamental areas of the Safety Case and scenario development using FEP. The most important factor in relation to the research question is whether the results can contribute to the optimization of the Safety Case or its components. Results on transdisciplinary processes *per se*, on the other hand, are presented in Ebeling et al. (2024).

3.1 Findings on the Safety Case in general

The Focus group recognized the difficult communication of safety to different target audiences in current Safety Cases as a problem. Modern Safety Cases would have an enormous amount of content. It would be almost impossible to read all documents down to the last detail. For this reason, there is a need for high-quality summaries at different levels with different lengths tailored for different target audiences (as, to some extent, already exist for some Safety Cases, e.g., for the French "Dossier 2005," cf. Andra (2005). These could be used in a multi-level documentation and communication system, for example, for communication and participation procedures. The central argumentation chain for safety in this must always be clearly recognizable. This means that it must be clear how the geology of the repository, the waste canisters, the geotechnical barriers and the repository design will ensure radiological safety for the biosphere in the long term. It is necessary to open up the Safety Case to interested citizens which means using easily and accessible language. According to the StandAG (2017), they have a legal right to a transparent document. Communication must be ensured across generations in view of the very long periods of time involved.

Also, risks in general should be better depicted in the Safety Case. For example, a comparison with risks in everyday life the audience is more familiar with would be useful. "Thumb-by-thumb" calculations juxtaposed to the complex model simulations in a Safety Case could also be useful for enhancing plausibility.

According to IAEA (2012), the term "Sicherheitsnachweis" (verbatim "proof of safety") has been used in Germany and Switzerland for "Safety Case". However, according to the Focus group the term "proof" is not well chosen, safety cannot be proven in the strict (mathematical) sense of the word. Instead, the term "safety report" would be more appropriate. Indeed, this term is already being used in German regulations.

The assessment period of one million years (as prescribed by German regulation) poses further challenges. Such a duration could be seen as hubris and thus would discredit other aspects of the Safety Case.

Some aspects of the Safety Case have taken on a life of their own. This is the case with the modeling of scenarios, where the level of detail might be distracting from the main purpose. The fundamental question should be asked as to whether all safety analyses must be carried out numerically or whether systematic methods are also suitable. An exclusive community is currently working on the Safety Cases. Experts from "outside the box" would be good for questioning ritualized procedures and offering criticism. In the future, some challenges (e.g., accessibility) could be solved digitally. The digital Safety Case also offers many opportunities in terms of communication.

In the German site selection procedure, the preliminary safety analyses as part of the Safety Case can also be suitable for making and comparing statements on long-term safety across repository host rock types.

For the PhD students' group, the assessment period of one million years is beyond human comprehension. They considered the word "safety" to be misleading. Quantification of safety was essentially a question of the probability that the repository system could or could not meet the necessary safety requirements. In other words: The group's discussion very much focused on probability, without further elaborating on the event(s) or consequences for which such probabilities might be considered.

The PhD students' group identified two further fundamental challenges. According to the group, societal problems can have a negative impact on the safety of the repository. Crises could require quick solutions. One solution could be an emergency plan for rapid closure of the repository. The PhD students' group also noted that the state of science and technology is constantly advancing. For example, quantum computers could revolutionize current modelling in just a few years' time. Since a Safety Case must meet the current state of the art in science and technology, the modeling in the Safety Case should be repeated before final closure. The review of the Safety Case should be carried out by an interdisciplinary committee consisting mainly of natural scientists and engineers. In addition, a ethics-related team with sociologists and social scientists would be appropriate. With regard to the structure of the Safety Case, the PhD students' group is in favor of dividing the report into two parts: It should be divided into the construction and operating phase and the post-closure phase. The group sees this as an opportunity to improve accessibility for non-experts.

3.2 Results on FEP-based scenario development

A remarkable optimization suggestion was made by the CWG in the exercise on FEP processing. Many modern FEP catalogs list the individual FEP one after the other. The references to other FEP are specified both analogously and electronically in a field provided for this purpose. This approach is inadequate in the opinion of the CWG. Instead, the suggestion was made that, in addition to the question of whether a dependency exists, the strength of this dependency as well as its likelihood and the knowledge evolution about it should also be indicated. Ideally, this should be done quantitatively, but at least qualitatively. In addition, it was suggested that the severity of the impact with regard to safety should also be presented. In discussions with the scientists involved in the workshop, matrix approaches were discussed as a way of addressing and representing the different effects (impact, its likelihood etc.) of FEP on each other (cf. Figure 3). The matrix is to be read in a clockwise direction. In this example, FEP 1 has a very large influence on FEP 2 and *vice versa*. FEP 2, for example, has a medium influence on FEP 3, but FEP 3 has no influence on FEP 2. According to CWE, this makes it possible to recognize significant dependencies immediately. In addition, uncertainties could be presented very clearly. Such approaches were utilized in past Safety Cases (cf., e.g., Bailey and Billington, 1998; Buhmann et al., 2008) but are currently not in use anymore. A "re-vitalization" was considered as promising, particularly in connection with digital data management.

Regarding the completeness of the FEP catalog, the evolution of microbes was mentioned. Microbes have the potential to significantly change chemical processes. It could not be ruled out that microbes would change over the course of a million years under the influence of radiation.

Another point worth mentioning were difficulties the CWG members had with certain terms, i.e., it turned out that there are ambiguities and lack of clarity in terminology. E.g., the difference between "waste inventory" and "waste matrix" was not well understood by CWG. Exchanges with non-scientists on a regular basis could help avoiding misunderstandings with respect to terminology.

For CWG, it is important that changes are carefully and permanently documented in FEP databases. In addition to the know-how, the know-why must be preserved in the long term. This is the only way to ensure that decisions made in the past can be understood by future researchers. Otherwise, it would always be necessary to go back and having to carry out the same work repeatedly. To achieve this, it would also be necessary for the managed databases to always be downward compatible. Regarding the composition of FEP expert groups, the CWG advocates opening them up to non-scientists. This is particularly important against the background of "future human actions." The societal FEP and scenarios during the operational phases (e.g., war or economic crisis) should also be considered. There should be no hierarchies or dependencies of any kind within the FEP expert groups. The broad scope of the FEP methodology is viewed rather positively by the CWG. However, with regard to the form of presentation, better visualizations for laypersons are needed. The exemplary reduction to a "good case," a "real case" and a "bad case" could be suitable for communicating FEP and scenarios.

At several points during the scenario development workshop, the CWG called for the use of digital tools in the Safety Case. One option would be the use of sliders in an interactive application, which adjust FEP severity. In this way, the effects of FEP could be presented in an easily understandable way in communication. FEP intended for future human actions should be displayed in such a program but grayed out. According to CWG, this is because it would be virtually impossible to exclude them, and the display would otherwise be misleading. In order to make the number of sliders displayed manageable, the CWG suggests automating a kind of preselection based on guiding questions.

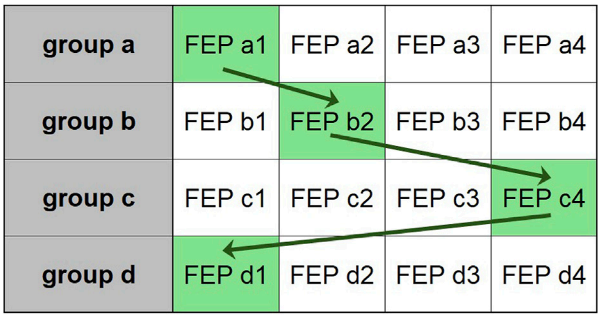

FIGURE 4
Morphological box as described by the PhD group. Groups a to d represent the result of a clustering of the FEP. This can be done, for example, according to their type (feature, event, or process) or their mode of action (e.g., chemical or physical). Shown here in green is an example of a path from FEP that results in a scenario. Group a could, for example, include different climate developments, group b the long-term geological behavior of the host rock, group c the early failure of the repository container at different times, and so on. By considering all possible paths (shown as arrows), the probability of occurrence for the resulting scenarios can be determined.

Another suggestion was to employ a software tool which allows to guide and to trace experts' discussions during scenario development. The suggestion was motivated by the CWG members' experience that, due to their multitude, discussion threads about scenarios could easily get neglected or forgotten. At this point, the TRANSENS scientists were again reminded of a tool which once was developed but is no longer in use: The FANFARE software described by Bailey and Billington (1998).

During the workshop on scenarios, the CWG also dealt intensively with the importance of microbes for the repository system, but in particular for the corrosion behavior of the waste containers. Ideas such as the structural installation of chemical traps were suggested as possible countermeasures.

The PhD students' group, that was not familiar with the FEP method at this point, proposed the creation of an FEP catalog that is as comprehensive as possible. International comparisons could be carried out for this purpose. Furthermore, the FEP catalog should be public in order to give as many people as possible the opportunity to add further FEP. A proposal was made for a reward system for identifying new FEP. Such rewards are currently paid for finding IT security vulnerabilities, for example. If individual FEP are too irrelevant, the group recommends removing them from the catalog, but this must be traceable and documented. The FEP should then be clustered by topic for the creation of scenarios. Subsequently, initial FEP should be identified for the scenarios to be developed. Particular attention should be paid to the temporal relevance of individual FEP for the respective scenarios. The PhD students' group sees a special case in the vicinity of the final disposal container. Only a few FEP are relevant for this area, so those scenarios should be calculated separately.

The group proposes the use of a "morphological box" as a method for evaluating the connections between the FEP and for processing the FEP into a scenario (Figure 4). Paths describing the scenario could be drawn in this box. These paths must be labelled with probabilities. All scenarios obtained in this way could be compared with a standard scenario in order to classify them in terms of their safety. However, it would first be necessary to evaluate all FEP and their interactions numerically. According to the PhD students' group, the scenarios created in this way should be analyzed by a committee. In particular, the time component should be considered: Not all FEP are relevant during the entire assessment period. If the scenario is too irrelevant, it should not be considered further in the safety analyses. However, the exclusion must be comprehensibly justified and documented. The PhD students' group recommends focusing on worst-case scenarios and best-case scenarios when communicating the results. When asked by the TRANSENS scientists about human intrusion, the group explicitly excludes scenarios of human intrusion or future human actions, as these could not be reliably predicted. According to current knowledge, a systematic approach could be carried out, but no serious mathematical calculation could be made.

3.3 Research results and digitalization of the safety case

As of now, Safety Cases are being produced, documented and published in traditional report formats, i.e., as printouts or their digital equivalents, e.g., as pdf documents. However, digitalization is an upcoming issue in the area of Safety Case production and publication. So far, such digitalization takes place in specific areas (e.g., in data management for modelling), but the vision of a digital Safety Case needs still to be developed.

From the workshop formats mentioned above many conclusions and suggestions arose which are not only generally expedient when aiming at optimization of the Safety Case but especially sensible (and in some cases only feasible) when implemented digitally. Moreover, they also have the potential to contribute to the vision of a digital Safety Case. Such suggestions concern both Safety Case production and documentation/communication and include (cf. the previous chapters):

- The organisation of a multi-level reporting system which allows to extract audience-tailored information and to trace e.g., argument chains through the wealth of information provided and, by such means, could ease both regulatory review and communication to interested audiences,
- The creation of interactive tools by which interested individuals could create and test their own assumptions concerning e.g., scenarios or parameter calculations for model runs,
- The creation of electronic tools for FEP processing which are e.g., able to record, systematize and document relationships between FEP in a much more comprehensive way than in current practices, and
- The creation of digital (and perhaps AI-based) tools able to systematically guide and record discourse and decision-making when developing scenarios.

These suggestions were presented to, and discussed at, a first workshop of OECD/NEA's Expert Group on a Data and Information Management Strategy for the Safety Case (EGSSC) on Safety Case digitalization in order to stimulate the development of visions for such digitalization (OECD/NEA, 2017, unpublished proceedings).

4 Discussion

Substantial input was obtained in all three working groups in order to improve the Safety Case in general and the FEP-based scenario development in particular. Due to the different focal points of the workshops, the work with the Focus group provided overarching results on communication and the methodology of the Safety Case. The CWG and PhD students' group primarily generated results on dealing with FEP and the scenario development resulting from them. The results obtained confirm some of the procedures already practiced today. For example, the use of the term "proof" is rarely found in modern Safety Case documents. The PhD student's group's proposal to compare FEP catalogs internationally is also already being practiced in this form. The idea of using a matrix for FEP processing and specifying quantitative dependencies can already be found in a similar form in Bailey and Billington (1998) and Buhmann et al. (2008) but has not been pursued further in nuclear safety research in recent years. The concept called for by the PhD group for rapid closure of the repository in the event of incidents such as war already exists in a similar form in Switzerland. Optimization proposals for the construction phase, operating phase and post-closure phase also already exist in some countries. Nevertheless, optimization proposals that have not yet been considered or have only been considered to a limited extent have been formulated. The fact that all working groups were able to generate such concrete proposals in a comparatively short period of time, and in the case of the CWG and the PhD student group without significant systems knowledge, proves the suitability of transdisciplinary approaches even for such complex research questions.

4.1 Cross-group findings

The digitalization of the Safety Case is an important topic for both the Focus group and the CWG. Possibilities for the use of modern computer technology were identified. The slider system requested by the CWG is a good example of this. It is interesting to note that the proposed options for a digital Safety Case were developed primarily with a view to the communication capability of the documents and only secondarily regarding to safety. To improve the accessibility of the safety case, both the focus group and the CWG see the need to provide short, high-quality summaries. However, the improved communicability and easier accessibility of the Safety Case will not only beneficial for interested members of the public; supervision and licensing authorities will also be able to review such a document better and probably more quickly.

The CWG and PhD students' groups also made similar demands when considering FEP. Although the selected matrix representation of FEP and the application of the morphological box differ from each other, it is very clear that the current approach using FEP catalogs was not sufficient for both groups. Instead, forms of representation were developed that provide a better overview and at the same time can show the influence of the FEP on each other. Another clear common ground was the demand for the documentation of know-how and know-why. This is an understandable and justifiable demand, particularly in view of the long time periods required to create Safety Cases. However, in addition to cross-group results, different views of the individual groups also became clear. There were clear differences between the CWG and PhD students' groups regarding the composition of a selection committee for FEP and scenarios. This shows that depending on the knowledge background, different priorities are placed on the composition of such a committee. For this reason, the professional composition of such a committee should be as broad as possible in order to cover the requirements of the stakeholders. The opinions of the groups also differed regarding the need to consider human intrusion. This could be due to the fact that the PhD students' group has specific knowledge in the field of modeling and could be aware of the difficulties in modeling future human behavior. Regardless of the potential causes of these demands, a fundamentally different view is revealed here. The question of whether and how human intrusion can or must be considered in the Safety Case could not be conclusively clarified and must be the subject of future research.

4.2 Opportunities and limitations

When evaluating the transdisciplinary research results regarding the optimization potential for the further development of the Safety Case, there are three problems. Firstly, it must be ensured that the results do not violate regulations applicable at the time. This becomes clear in the debate about the assessment period of one million years. Both the Focus group and the PhD students' group described this as difficult to communicate. Nevertheless, the German Safety Case must cover this period, as it is a legal requirement by the Site Selection Act. The second challenge is the feasibility itself. It is to be expected that some proposals cannot currently be implemented technically, or only partially. The required use of automated selection of FEP and the subsequent use of sliders in the presentation of processes is an example of this. The implementation of this proposal would *de facto* imply the graphical representation of the entire scenario modeling. The computing capacities for this would be enormous and implementation would only be possible in part given the current state of IT development. The third issue to be considered is the lack of representativeness of the research results (cf. Heiermann and Olszok, 2024). For example, just because the consideration of microbes and their evolution in the repository system was particularly important to the CWG does not mean that it should be to other citizens without system knowledge. It would be a logical mistake to conclude from the results that all those affected with similar types of knowledge would have made the same suggestions for improvement – transdisciplinary research does not necessarily generate reproducible results. Nevertheless, the research work in TRANSENS made it possible to formulate specific suggestions for optimization: The TRANSENS researchers found many suggestions sensible and worth pursuing. Their value is based, at least in part, on the fact that the perspectives, and knowledge types of the workshop participants were diverse and, in part, different from those of the specialists. The suggestions have been, or will be, taken to the SC specialist community, where their value and usefulness can be tested. The fact that a large number of substantial results were achieved proves that the transdisciplinary approach can also be successfully applied in the area of Safety Cases. Future safety analyses carried out during the German site selection procedure, including the Safety Case, may have the opportunity to benefit from these research results.

5 Next steps in TRANSENS and beyond

After the CWG and PhD students' groups have made specific proposals for dealing with FEP and creating scenarios, these are to be evaluated by the specialist community. To this end, another workshop will be held with experts in the field of Safety Case creation, at which the research results will be presented. The aim is to find out which proposals are suitable for adoption in the practice of Safety Case creation. If the proposed methodologies are not found to be feasible, suggestions could be developed as to how the required objectives could be achieved in other ways.

The aim of the research project is also to feed the transdisciplinary results back into the Safety Case community. Results have already been presented within the framework of the *Expert Group on a Data and Information Management Strategy for the Safety Case* (EGSSC) and the German implementer BGE (Federal Company for Radioactive Waste Disposal).

Data availability statement

The datasets presented in this article are not readily available because the protection of individual rights of the participants could not be guaranteed. Requests to access the datasets should be directed to marcel.ebeling@tu-clausthal.de.

Ethics statement

Ethical approval was not required for the studies involving humans because The research is exempt Category 2 - Educational Tests, Interviews, Surveys, Observation of Public Behavior. 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

ME: Conceptualization, Investigation, Visualization, Writing–original draft, Writing–review and editing. MH: Investigation, Writing–review and editing. K-JR: Conceptualization, Funding acquisition, Investigation, Supervision, Writing–original draft, Writing–review and editing.

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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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