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A unified approach to Performance Assessment (PA) of geological CO_2 storage

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Abstract

Performance Assessment (PA) evaluates the effectiveness of a specified system or sub-system relative to some criteria of interest to particular stakeholders. A flexible PA approach has been developed for geological CO_2 storage, by which qualitative information, quantitative data, output from numerical models and expert judgments are combined within a decision-support framework. The methodology has been implemented in three software tools: (1) TESLA, which is used to construct decision trees, propagate evidence and record the logic underlying a decision; (2) an on-line database of Features, Events and Processes (FEPs) targeted at CO_2 storage; and (3) QPAC-CO2, for modelling system performance.

*Keywords:*Performance Assessment; Decision support; Numerical models; Features Events Processes

1. Introduction

Performance Assessment (PA) has been defined slightly differently by many authors (e.g. Maul et al. [1]), but generally it can be considered the evaluation of the performance of a specified system or sub-system relative to some criteria of interest to particular stakeholders. The performance measures depend upon the stakeholders and their goals. A regulator interested in safety may assess an entire storage system and its surroundings, and a risk of leakage may indicate system performance. Alternatively, a drilling engineer might consider only the performance of well seals and a corresponding performance measure might be the length of time for which a seal will be effective. If operational safety is being assessed, relevant timescales are tens of years; if the effectiveness of climate change mitigation is being evaluated periods in the order of 10^3 years may need to be considered.

Generally, it is impractical to predict accurately values for the performance indicators of interest, either for computational reasons, or for reasons of epistemic uncertainty (uncertainty caused by lacking knowledge) and

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aleatory uncertainty (uncertainty due to inherent natural variability). In any case, accurate predictions may be unnecessary provided that it can be demonstrated that:

- values determined for performance measures will not violate the performance criteria of interest within the considered timeframe; and / or (depending upon the purpose of the PA)
- inevitable uncertainities in performance measures have been recognized and taken into account.

For example, a regulator might be satisfied if it could be established that, taking into account uncertainties, maximum (conservative) estimated leakage rates from the primary storage reservoir are sufficiently small that there would be no adverse impacts. On the other hand, an engineer planning an injection project might be more concerned to identify the sources of uncertainty in estimates of a reservoir's CO_2 storage capacity, thereby enabling data acquisition to be targeted effectively.

However, it is often challenging to quantify the uncertainties in performance indicators, because of the complex coupling that exists between the various processes that will affect a CO_2 storage system. For example, without undertaking coupled simulations the consequences for performance of mixing between injected CO_2 and formation water are unclear. In this case, the chemical reactions will be enhanced by the acidic conditions in the mixing zone and, depending upon the compositions of the reservoir rock and formation water, may include removal of CO_2 from the fluid phase by precipitation of carbonate minerals. Under these circumstances there is a coupling between fluid flow (CO_2 injection and water displacement), dispersion (mixing between CO_2 and water) and chemical reactions. It is necessary to determine whether the net effect will be positive with respect to performance (e.g. because effectively CO_2 is immobilized permanently) or negative with respect to performance (e.g. because there is a loss of reservoir porosity and / or permeability, causing decreased injectivity and / or storage capacity). Furthermore, processes operating at a small spatial scale may have uncertain consequences at larger spatial scales. For example, if the small-scale stress fluctuations that occur within a reservoir during CO_2 injection cause opening of pathways for fluid flow, there might be larger-scale CO_2 migration.

In practice, bounding values of performance measures must normally be calculated using a suite of different numerical models in such a way that the strengths and weaknesses of the different models complement one another. Each model is optimized for a particular purpose and lies within a spectrum of complexity. At one extreme lie finely discretized models of small spatial scales (e.g. models of well seal evolution) that represent all the major processes operating within the modelled domain (detailed models); at the other extreme are coarsely discretized models of the entire system of interest that represent only a sub-set of the key processes (system models). The codes used to calculate performance measures are generally of the latter type and, being simplified, can be used to gain insights into the coupling between processes. The detailed models are used to inform the system models by: building understanding of key physical processes that affect specific parts of the system; analyzing uncertainties; and providing outputs that might be used as inputs to other codes. Confidence in the validity of the performance measures must be built using varied quantitative information (including numerical model outputs), qualitative information, expert judgments, and multiple lines of reasoning. This paper presents a flexible and structured approach that has been designed to meet these goals.

2. Related Performance Assessment Tools

2.1. General Approach

The general approach recognizes that during a CO_2 storage project performance measures are used to support decisions, and that the nature of the decisions vary during the lifetime of a storage project. Examples include:

- a decision to target data acquisition so as to reduce some area of uncertainty that is important for PA;

- a decision to proceed with injection, based on an initial assessment of performance; and
- a decision to pass responsibility from an operator to a competent national authority, such as a government agency (probably at some time after CO_2 injection has ceased and following a period of monitoring).

The decision-making process needs to be transparent and readily related to the various stages of the PA (Figure 1). Each decision must be justified by providing an audit trail referring to the models and / or expert judgments that underpin it, through scenario development and analysis of Features Events and Processes (FEPs), to an underlying knowledge base. Here, FEPs are factors that are used to describe the nature and behaviour of the system of interest. There are many slightly different formal definitions of the term 'FEP' (e.g. Savage et al. [2]), but fundamentally:

- A 'Feature' is a physical component of a system (in the context of CO_2 storage, 'reservoirs', 'caprocks', 'wells' and 'pore fluids' would be features of the system).
- An 'Event' is a process that influences the evolution of the system over a time period that is very short compared to the time frame being considered ('borehole completion' would normally be considered to be an 'event').
- A 'Process' is a dynamic interaction between 'Features', which may operate over any particular time interval of interest.

The definitions of 'Events' and 'Processes' overlap and the time frame being considered will largely determine whether or not a phenomenon is classified as an 'Event' or a 'Process'. FEPs can be used as 'building blocks' to develop scenarios, each of which describes a possible future state of the CO_2 storage system and / or a future event that might impact upon the system. Standardized databases of FEPs can also be used to audit scenarios and system level models.

The approach uses a decision-support software tool (TESLA), which is linked directly to a project-specific database of FEPs. The flexible general-purpose modelling code QPAC-CO2 may be used to implement both detailed models and simplified, abstracted system-level models. Outputs from both kinds of model may be used to inform expert judgments that are inputs to the decision-support tool.

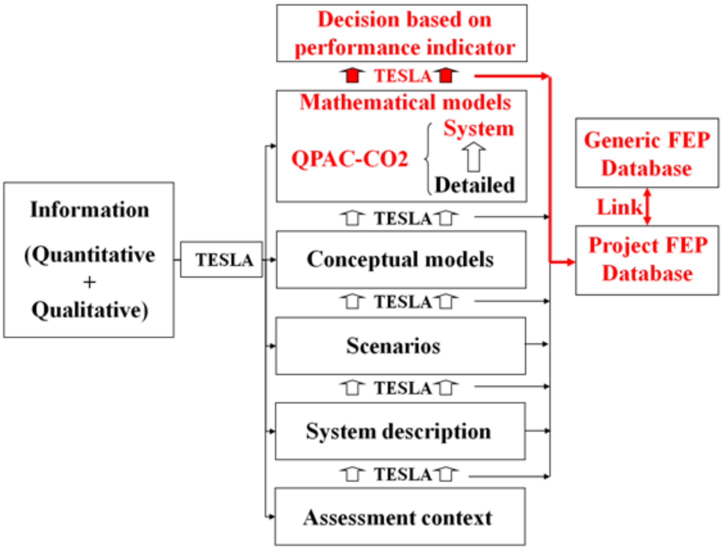
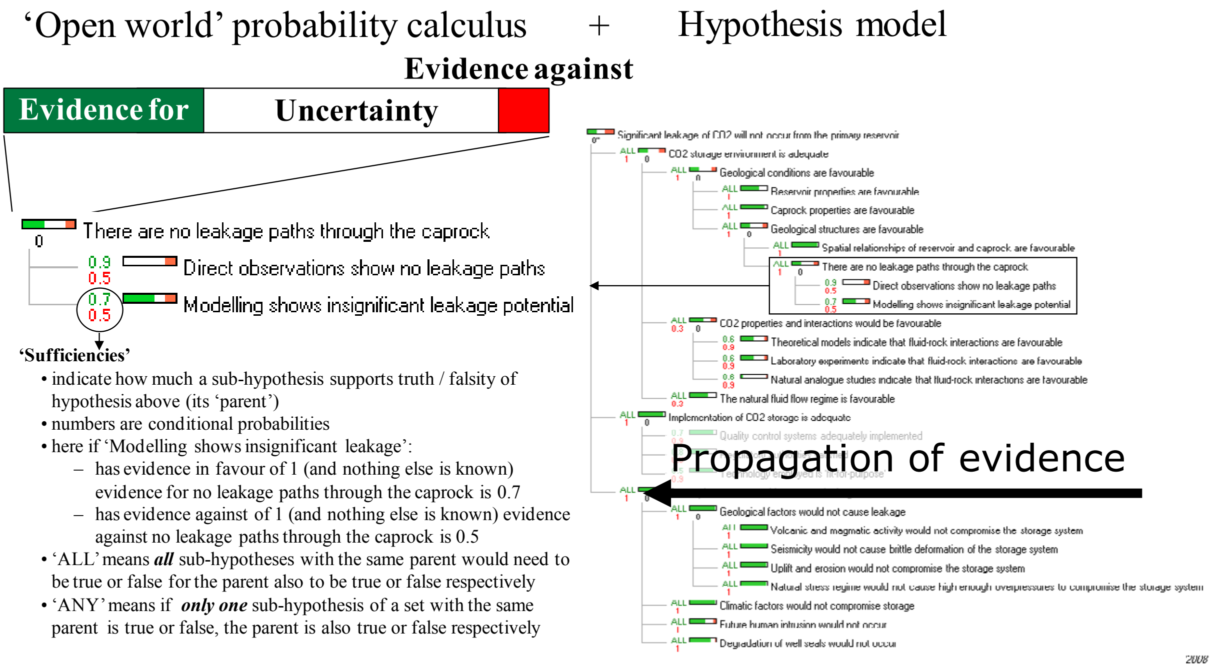


Figure 1 Schematic illustration of the relationships between major components of a PA, showing the stages where the software tools described in Sectons 2.2, 2.3 and 2.4 can be used. Red highlighting shows where the examples described in Section 3 fit into the overall PA framework.

2.2. Decision Support Tool (TESLA)

The decision-support tool TESLA [3] implements Evidence Support Logic (ESL) which has been described previously in Davis and Hall [4] and Bowden [5] (Figure 2). The method involves constructing decision trees to reflect: (1) the PA's context (i.e. the decision depends on the storage project's stage of development and the aims of the stakeholders); (2) the FEPs that may influence the system being evaluated; (3) the kinds of information that enable judgments to be made concerning the characteristics and effects of interactions among these FEPs. The decision tree consists of a hierarchy of hypotheses (a hypothesis model), which links the main hypothesis of interest (e.g. that there will be insignificant CO_2 leakage from a deep storage reservoir) to data or information (e.g. geological evidence for the existence of a cap rock, experimental evidence for the effective sealing of boreholes, output from supporting modelling studies etc), usually via intermediate hypotheses. The 'evidence' for or against each hypothesis is the extent to which information leads to confidence in the hypothesis' dependability or falsehood respectively. Inputs to a decision tree are independently chosen numerical representations of 'evidence' for and against the dependability of the hypotheses at the lowest level of the hierarchy. The 'evidence' may correspond to quantitative information (e.g. numerical model output, measurements in boreholes etc) or qualitative information (e.g. anecdotal evidence that a particular kind of borehole seal is effective). Each item of qualitative or quantitative information is then mapped to two values on a numerical scale of 0 to 1 representing evidence for and against. This representation of 'evidence' is a type of Interval Probability Theory, which employs three-value logic. The 'evidence values' are propagated logically through the tree, from the lowest level of the hierarchy to the top-level hypothesis. Accordingly, if the 'evidence' that a hypothesis is true is represented by the probability pT and the 'evidence' that a hypothesis is untrue is represented by the probability pF, then uncertainty U = 1-pT-pF. This approach contrasts with classical (point) probability theory, which requires that pT + pF = 1. Therefore, an advantage of ESL is that it distinguishes cases where data quality is poor, from cases where data quality is unknown.



'Sufficiencies'

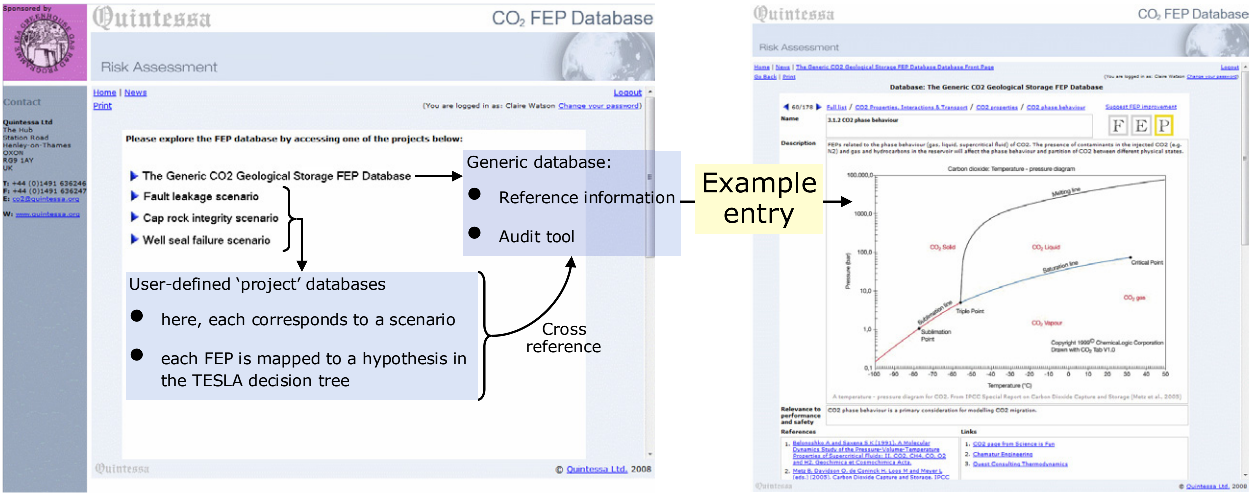
- indicate how much a sub-hypothesis supports truth / falsity of hypothesis above (its 'parent')
- numbers are conditional probabilities
- here if 'Modelling shows insignificant leakage':
  - has evidence in favour of 1 (and nothing else is known) evidence for no leakage paths through the caprock is 0.7
  - has evidence against of 1 (and nothing else is known) evidence against no leakage paths through the caprock is 0.5
- 'ALL' means ***all*** sub-hypotheses with the same parent would need to be true or false for the parent also to be true or false respectively
- 'ANY' means if ***only one*** sub-hypothesis of a set with the same parent is true or false, the parent is also true or false respectively

Figure 2 Simplified illustration of ESL, as implemented in the code TESLA.

2.3. Database of Features, Events, Processes (FEPs)

A generic FEP database has been developed specifically for the geological storage of CO_2 (Maul et al. [5]) and is available on the International Energy Agency (IEA) Greenhouse Gas website (http://www.co2captureandstorage.info/riskscenarios/riskscenarios.htm). The FEPs have been defined so as to be comprehensive in the sense that they are sufficiently general to cover all aspects of long-term safety and performance of the storage system. They are mostly relevant to the period after CO_2 injection has ceased and the following sealing of the injection boreholes, apart from some FEPs that describe those aspects of the injection phase that could affect long-term performance and the initial status of the storage system. The FEPs included in the database are not specific to any particular model. A particular FEP may be represented differently in different models, and will not necessarily correspond to a model parameter.

Recently added functionality allows separate project databases to be created within the on-line tool and then linked to the generic database (Figure 3). The approach is for experts to evaluate a particular storage site and define FEPs to describe the site and the potential future impacts upon it in their own language, based upon site-specific information. These FEPs are used to create a project-specific FEP database. Each FEP in this project-specific database can then be linked to one or more FEPs in the generic database. In this way, the generic FEP list is used as an audit tool to build confidence that all relevant topics have been considered when defining the project-specific FEP list. The knowledge-base that underpins the project-specific FEPs can also be accessed via links in each FEP entry. Similarly, the user is able to create a separate project-specific database that corresponds to each scenario that has been developed to describe a future state of the system. Each FEP in the scenario database can be linked to a corresponding hypothesis in a hypothesis model developed using TESLA (see Section 2.2).



Please explore the FEP database by accessing one of the projects below:

- The Generic CO2 Geological Storage FEP Database
- Fault leakage scenario
- Cap rock integrity scenario
- Well seal failure scenario

Generic database:

- Reference information
- Audit tool

User-defined 'project' databases

- here, each corresponds to a scenario
- each FEP is mapped to a hypothesis in the TESLA decision tree

Cross reference

Example entry

Database: The Generic CO2 Geological Storage FEP Database

Name: 3.1.2 CO2 phase behaviour

Description: FEPs related to the phase behaviour (gas, liquid, supercritical fluid) of CO2. The presence of contaminants in the injected CO2 (e.g. N2) and gas and hydrocarbons in the reservoir will affect the phase behaviour and partition of CO2 between different physical states.

A temperature - pressure diagram for CO2. From IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005)

Relevance to performance and safety: CO2 phase behaviour is a primary consideration for modelling CO2 migration.

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2. Metz B, Davidson O, de Coninck H, Loos M and Meyer L (eds.) (2005). Carbon Dioxide Capture and Storage. IPCC

Links

1. CO2 page from Science is Fun
2. Chematur Engineering
3. Quest Consulting Thermodynamics

Figure 3 The home page of the on-line FEP database, showing the relationship between the generic database and project-specific database (left) and an example entry in the generic database (right).

2.4. General -purpose modelling tool (QPAC-CO2)

For applications targeted at CO_2 storage, Quintessa has developed a collection of modules for its QPAC general-purpose modelling code (Quintessa [7]), collectively termed QPAC-CO2. These modules are tailored to simulating specific fundamental processes and new processes can be added easily. Individual modules can be combined to represent coupled phenomena. The current suite of processes includes multiphase flow, reactive geochemistry (including solid-solution models and Ostwald ripening processes) and thermal evolution processes. The code can be used flexibly to simulate the relevant coupled chemical and physical processes at both the detailed level and system level. Modellers are able to solve the governing equations for a range of problems including those with strongly coupled non-linear processes. Using the code it is possible to undertake probabilistic calculations, using several computers simultaneously if necessary.

QPAC-CO2 implements a flexible approach to system discretization. The modelled system can be divided into a number of subsystems and within each one the set of processes to be modelled is defined. The user is able to specify the extent to which these processes are coupled. In a systems-level model, different subsystems will often be used to represent different parts of the system, with different types of processes being modelled in each one. In a detailed model, different subsystems can be used to break the system down, thereby reducing the number of variables for which solutions are required. Each subsystem can be spatially discretized using either a traditional space-filling approach or an abstract compartmentalization, or a combination of both. Subsystems are linked by joiners, which control how quantities simulated in one subsystem affect, or are transported into, another subsystem.

3. An Integrated Approach to PA

A simple example is used to illustrate how the software tools described in Section 2 can be used together. Figure 4 compares spatial variations in post-closure CO_2 saturation in a deep sedimentary rock reservoir, as simulated by a finely discretized standard reservoir model and a simplified, coarsely discretized QPAC-CO2 model. Expert evaluation of information about the reservoir suggested that undetected fluid flow pathways might occur through the caprock. Sensitivity studies using the simplified QPAC-CO2 model investigated the potential significance of leakage through these possible features (Figure 5). The model used for these studies was parameterized using a combination of site observations and expert judgments based upon them.

The possibility that the modelled leakage paths actually occur must be judged by experts, based on site data, fundamental theory and their previous experience. Thus, an evaluation as to whether or not leakage is significant requires a combination of model calculations with expert judgments based on qualitative and quantitative information. Figure 6 gives a simplified example of how this can be achieved using the TESLA code and shows three hypotheses that are taken from the larger tree in Figure 2.

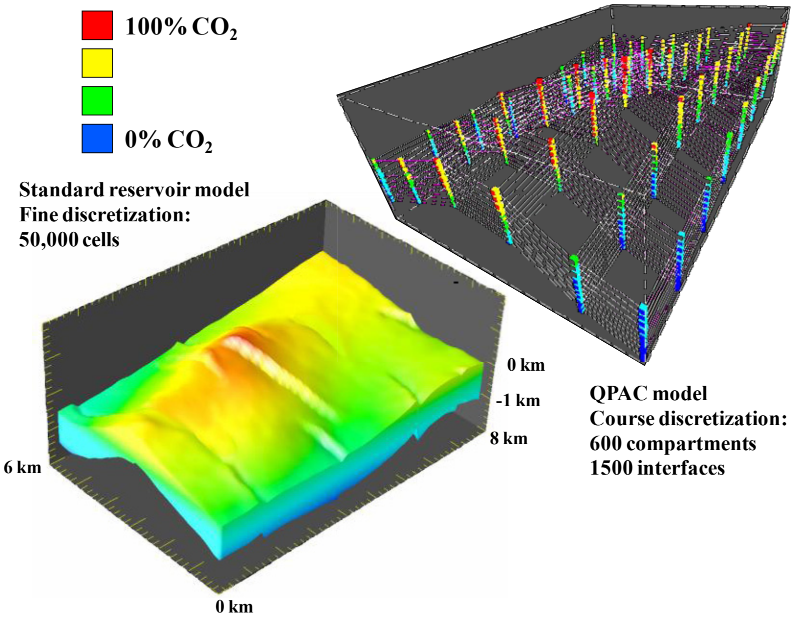

Figure 4 Illustration of a finely discretized reservoir model (left) and a simplified, coarsely discretized QPAC-CO2 model (right) showing the spatial distributions of CO_2 following completion of CO_2 injection. The two sets of model output are mirror images.

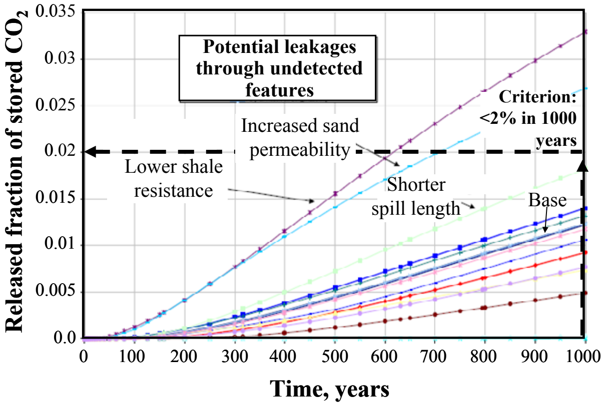

Figure 5 QPAC-CO2 calculations to evaluate the potential significance of leakage through undetected features in the caprock. The fraction of stored CO_2 that could leak from the reservoir is shown as a function of time for alternative hypotheses concerning undetected leakage pathways.

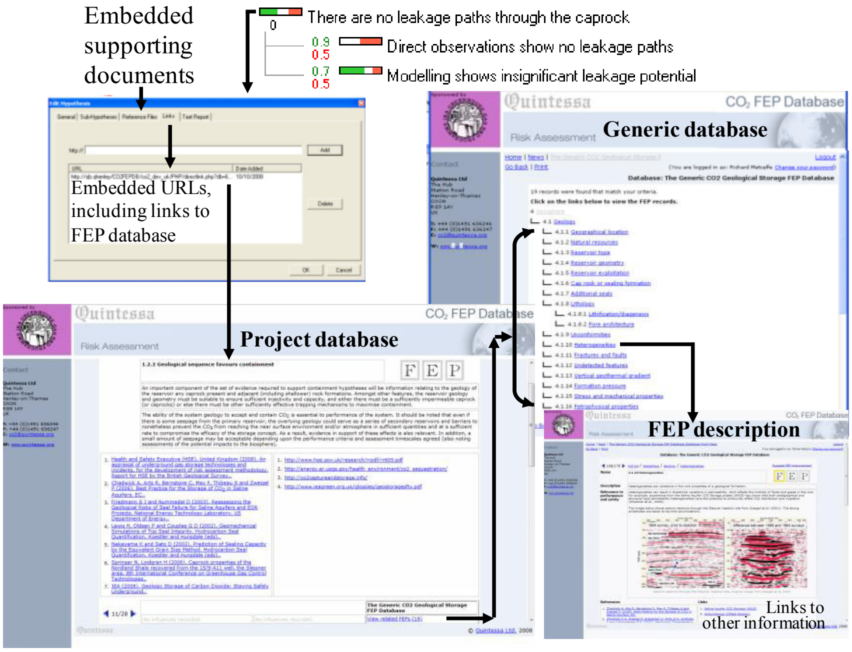

Figure 6 Example showing how a TESLA decision tree can be used to combine judgments based on different kinds of information (here direct observations and QPAC-CO2 model output). The judgments are documented and justified by embedding supporting information in the decision tree and by linking hypotheses in the tree to an on-line project FEP database that describes a cap-rock failure scenario.

Here, the parent (top-level) hypothesis is that there are no leakage paths through the caprock. One of the sub-hypotheses is that no leakage paths are observed directly. However, faults were detected by seismic surveys (Figure 4) and could potentially form pathways, although there is no direct evidence that in fact they leak. Therefore, the 'evidence against' this hypothesis being true is set to 0.5, as shown by the red bar in the graphical representation of the hypothesis. Uncertainty as to whether or not there is actually leakage is shown by the white space that occupies the other 0.5 of this representation. In contrast, the modelling results can be interpreted in terms of 'evidence for' and 'evidence against' the sub-hypothesis that 'modelling shows insignificant leakage potential'. If the criterion for this hypothesis being true or false is that <2% of the initially stored CO_2 will leak from the reservoir in 1000 years, then most model cases indicate the hypothesis to be true (Figure 5). However, if leakage occurs through a hypothetical relatively high-permeability shale or sandy sedimentary stratum within the caprock, then the hypothesis could be false. In these cases, the overall judgment of leakage potential must be based on both the modelled consequences of the hypothetical conductive features, and an assessment of the likelihood that these features actually occur, giving ‘evidence for’ of 0.6, ‘evidence against’ of 0.2 and residual uncertainty of 0.2.

TESLA also provides several tools for representing and / or analyzing uncertainties associated with a decision. One example is the ‘tornado plot’, which shows the sensitivity of the ‘evidence for’ and ‘evidence against’ the highest-level hypothesis, to incremental variations in the ‘evidence for’ and ‘evidence against’, respectively, of each lowest-level hypothesis (Figure 7).

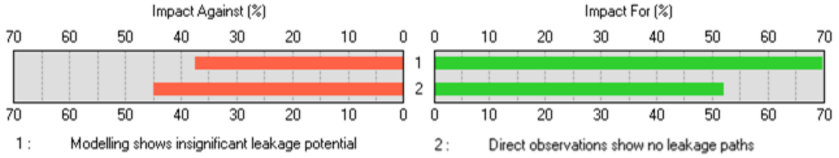

Figure 7 Example ‘tornado plot’ corresponding to the simple decision tree in Figure 6.

4. Conclusions

When applied to CO_2 storage, the term ‘Performance Assessment’ (PA) means different things to different stakeholders. Furthermore, PA is typically a complex process that uses site information, both quantitative and qualitative, numerical models and value judgments of experts involved in different aspects of storage. This paper has presented a flexible framework that allows integration of all these diverse kinds of information and that can be adapted readily to meet the needs of a particular stakeholder or group of stakeholders. The framework can be used throughout a CO_2 storage project, not only to evaluate the overall performance of all or some aspect of the project, but to aid planning of each stage, based on information available from the previous phase.

5. References

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