Methodological guidelines for risk assessment

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2. Executive summary

This report details the method that will guide the work performed as part of work package (WP) 5 "Safety and performance" of the PilotSTRATEGY project. A robust and shared method for risk management is needed to increase the chance that future CO_2 geological storage pilots can be operated with the highest level of safety and performance.

The method relies on several principles. The main reference for risk management in general is the ISO31000 norm on risk management. It contains useful recommendations applicable to a broad range of situations, and the process detailing the activities of risk management is the basis of the PilotSTRATEGY method. ISO31000 is not prescriptive in terms of methods, however, authors have highlighted that a robust risk management effort should include quantitative risk analysis. A review of the risk assessment principles of the CCS directive is also provided. The PilotSTRATEGY method thus aims to be quantitative, with the goal of fulfilling the directive's objectives.

The PilotSTRATEGY method is iterative. At least two "rounds" should be performed, allowing for an optimal allocation of effort and resources. Both rounds follow the same process:

1. First, an experimental design step creates a discussion on what risks should be studied and how they will be computed
2. The second step aims at computing the risks, using all the resources available, including numerical models, data analysis and expert judgement
3. The third step is a decision analysis step: considering the current knowledge of the risks, provide recommendations regarding:
    a. New knowledge to be acquired
    b. Measures to control the risk (design or corrective measures)
    c. Monitoring
4. Stakeholders should be engaged as much as possible, in collaboration with WP6

Tools and example are provided for more guidance regarding these steps:

- A method for building risk scenarios using bow-tie diagrams
- Examples of risk analysis using Monte Carlo simulation
- Overview of Value of Information and Decision analysis with example relevant to CO_2 storage

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3. Introduction

The goal of PilotSTRATEGY is to characterize potential CO_2 storage sites in three main countries: France, Spain and Portugal. Safety and performance risk management is a crucial aspect in this preliminary step and its practice needs to follow a common framework so that experience can be shared between countries and replication in other countries is facilitated.

This report seeks to develop this common methodological framework for safety and performance risk management.

The report is written from the more general to the more specific. In the next paragraphs, we will expose the purpose of risk management activities as well as go back to the main definitions. The next chapter is dedicated to the main principles and references for risk management, including specificities of CO_2 storage. We will then develop and explain the method specific to the PilotSTRATEGY project. In chapter 6, we will provide concrete tools and example for applying the PilotSTRATEGY method.

3.1 Purpose of the "Safety and performance" work package

The work packages of PilotSTRATEGY are organized around a typical workflow for characterizing a CO_2 storage site. The main objective of the "Safety and performance" work package (WP5) is to ensure that the characterized sites will be able to operate with the highest safety standard, meaning that any impact or risk to people and the environment should be kept at a minimum level. In addition, the work package also consider the overall performance of these sites as the primary objective is to store large quantities of CO_2 in the subsurface.

In order to achieve the safety and performance objectives, we use risk management methods. The main purpose of these methods is to provide a robust and tested framework for checking that the objectives of the project will be met.

It is not uncommon to see terms such as safety, risk, uncertainties, etc. being used interchangeably. We provide the definitions below in order to be specific regarding the meaning for those words that will be used repeatedly in this report.

3.2 Definitions and concepts

Safety

A state where those conditions that can cause death, injury, occupational illness or damage to or loss of equipment or property, or damage to environment has been reduced to a level generally accepted (Rausand, 2013).

Performance

The performance of a project or system is what contributes to meet the objectives (of the project or system). Alternatively, performance can be defined as the ability (of the project or system) to meet the expectations of the stakeholders.

Usually, performance is composed of several objectives such as technical, economic or environmental performance. As such, safety objectives are included in the global performance of a system (as most

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stakeholders expect that the system will be safe). Performance is commonly measured by a set of performance indicators. As an example, one of the main indicator for measuring the performance of a CO_2 storage site is the quantity of CO_2 stored over time. Many other indicators can be used: maximum pressure, extension of plume, leakage risk, etc.

Stakeholders

Any person or organisation that is affected by the project or system.

Uncertainties

It refers to an absence of certainty about a situation or an outcome. When the true result is not known.

Example: Storage capacity has a 90% chance of being between 100Mt and 600Mt

Some authors distinguish between:

- *aleatory uncertainty. Uncertainty inherent in a phenomenon.*
- *epistemic uncertainty. Uncertainty attributable to incomplete knowledge about a phenomenon, which affects the ability to model it,*

with the idea that only the latter can be reduced. This distinction is not always practical.

Risk

Risk is the effect of uncertainty that would prevent to reach an objective. The possibility of a loss to something of value.

Example: there is a 20% chance that the objective of 200Mt capacity is not reached (and the project is not viable).

The risk concept has two dimensions:

1. *The probability that harmful events will occur*
2. *The consequences of these events*

Sometimes, risk is summarized by computing an expected value of the loss, but this is a loss of information with respect to the representation of risk as a vector (D. W. Hubbard, 2009).

Impact

It is the (positive or negative) effect of the project or system on health or on the environment.

There is often a confusion between risk and impact. Usually impact is not affected by uncertainty. Example: the well rig will impact the landscape. Environmental risk is the possibility of a negative impact (e.g. possibility of pollution in case of a leak).

Hazard

Source of potential harm

Example: a large quantity of CO_2 is a hazard as it could be a source of massive leakage. It is not necessarily a high risk when there is little likelihood that this hazard would provoke harm.

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Risk management

Coordinated activities to direct and control an organization with regard to risk (ISO, 2009).

The above definition is generic and applies to any type of risk. For safety risk management in particular, the following definition applies: All actions taken to achieve, maintain or improve the safety of an installation and its operation.

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4. Principles and references

In this chapter, we review the main principles for risk management. The first paragraph is dedicated to the international norm on risk management: ISO 31000. The second paragraph is a quick focus on the distinction between qualitative and quantitative risk management, as it is an objective of PilotSTRATEGY to increase the practice of quantitative methods. In the third paragraph, we review the requirements of the European CCS (Carbon Capture and Storage) directive in terms of safety risk management.

4.1 ISO 31000 on risk management

The ISO committee has issued a norm on risk management: ISO 31000, which was revised in 2018 (ISO, 2018). It is a high-level standard providing guidelines for risk management and is applicable by any organizations, to any type of risk. The main chapters of the norm describe principles, framework and process of risk management. We will briefly describe the process here:

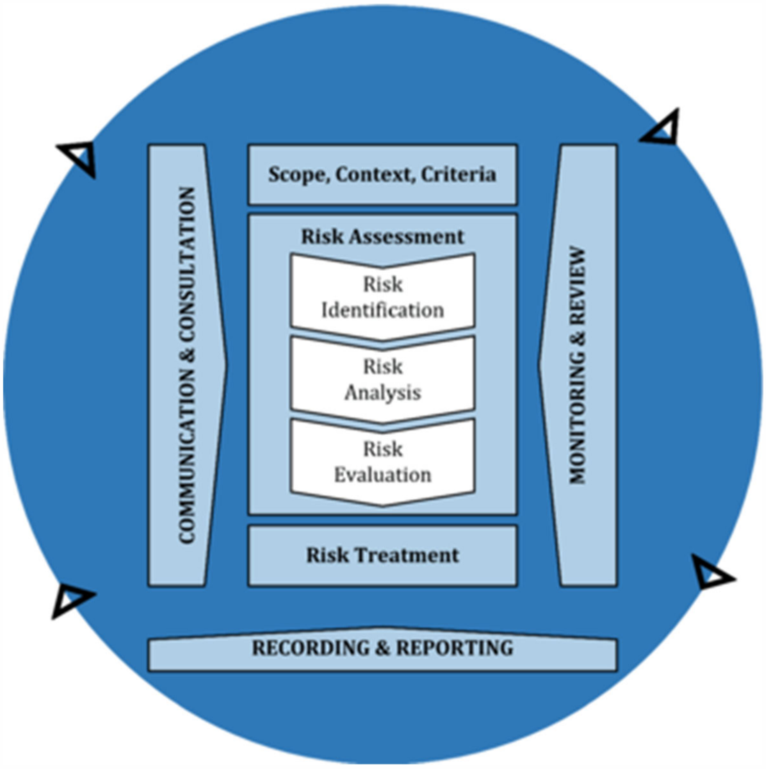

Figure 1: risk management process. Source: ISO (2018)

This process is mostly iterative even though it is often presented as sequential steps. Risks are dynamic in nature so the process needs to be continuously applied to correspond to these risks.

4.1.1 Communication and consultation

Communication and consultation should be maintained with stakeholders during all the stages of the process. ISO (2018): “Communication seeks to promote awareness and understanding of risk, whereas consultation involves obtaining feedback and information to support decision-making.”

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4.1.2 Scope, context, criteria

The initial step is to be clear about the scope of risk management and the context in which it is applied.

Criteria are guides to decision-making and allow to specify when risks are acceptable relative to the objectives. It is important that criteria are discussed with stakeholders before analysing the risks.

4.1.3 Risk assessment

Risk assessment is composed of three steps according to ISO (2018): risk identification, risk analysis and risk evaluation

4.1.3.1 Risk identification

The first step of risk assessment is risk identification, and the objective is to provide the list of risks that will be considered in the rest of the process. This step should be continuously updated as new information emerges. Many techniques can be used to identify risk.

4.1.3.2 Risk analysis

The purpose of risk analysis is to comprehend the nature of risks, often in terms of likelihood and potential impact. The analysis can be qualitative or quantitative depending on the resources available, the objectives, and the context.

4.1.3.3 Risk evaluation

The purpose of risk evaluation is to support decisions. In theory[1], one should compare the result of risk analysis with risk criteria and determine if the risk is acceptable in the current state or need treatment (reduce the level of risk), or more information (reduce uncertainties).

4.1.4 Risk treatment

Treating the risk usually means to act on its level (through reduction of likelihood or severity), but there is a variety of decisions that can be made (such as seeking more information or contracting insurance). Choosing the best treatment from a list of potential solutions is a complex decision, and should broadly take account of the various costs and benefits to different stakeholders.

4.1.5 Monitoring and review

Monitoring here is not necessarily "technical" (not to be confused with monitoring of a CO_2 storage site) but involves observing the risks and the risk management process. Regular review is necessary to ensure that the process always use the best available information, and seek any opportunity to improve the process itself.

4.1.6 Recording and reporting

All information about the process should be easily available and reported to various stakeholders. The level of information should be adapted to the particular stakeholders.

4.1.7 Conclusion

ISO 31000 does not prescribe any particular technique but provide good guidance regarding the overall process. The method implemented in PilotSTRATEGY is fully in line with this process.

[1] In practice, risk criteria and risk analysis are rarely both quantitative and thus the comparison is mostly qualitative

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4.2 Qualitative and quantitative risk management

ISO 31000 does not impose any view regarding the application of qualitative or quantitative methods to risk management. In general, this refer more specifically to the risk analysis step (see paragraph 4.1.3.2). In this section, we will briefly describe both methods and explain why we advocate for quantitative methods in the scope of PilotSTRATEGY.

4.2.1 Qualitative methods

A qualitative risk analysis means that the likelihood and severity of a risk is discussed on qualitative grounds only. For instance, it may make use of words such as “not likely” or “probable”. One of the most used technique is to use an ordinal scale such as 1 to 5 with 1 being least likely and 5 being most likely. A similar scale can be used for the severity of the risk.

Sometimes, the scales are “semi-quantitative” (but we consider it belongs to the qualitative category), by providing numbers for assigning the score. An example of two semi-quantitative scales, assembled in a typical risk matrix is provided in Figure 2.

Probability	P - Rating	P - Indices						
> 40%	6	Likely						
20% < p <= 40%	5	Occasional				Severe Losses		
10% < p <= 20%	4	Seldom						
5% < p < = 10%	3	Unlikely					Well Control	
1% < p < = 5%	2	Remote						Blowout
<= 1%	1	Rare						
Consequence Rating			1	2	3	4	5	6
Consequence Indices			Incidental	Minor	Moderate	Major	Severe	Catastrophic
Consequence Cost			<= USD 100K	USD 100–250K	USD 250K–1MM	USD 1–5MM	USD 5–20MM	> USD 20MM

Figure 2: example of a risk matrix using two semi-quantitative scales (Thomas et al. 2013)

Usually, risk matrices also provide the risk criteria by using a colour code (also displayed on Figure 2): green means the risk is acceptable, red means that risk treatment must be put in place, and yellow means either active monitoring or reduce if practicable.

Many authors have warned that the use of risk matrices can be misleading and should be avoided in general (Cox, 2008; D. Hubbard & Evans, 2010; Thomas et al., 2014). They recommend to either stay qualitative if it is enough (i.e. only describe risks using words instead of numbers and rank them manually) or to fully quantify the risk. They argue that using ordinal scales introduce errors, and can lead to rank reversal. For instance in the example of figure 2, Thomas et al., (2014) show that the “Severe Losses” risk is actually less than the “Blowout” risk whereas the former is classified in “red” and the latter in “yellow”. We describe the quantitative method in the next section.

4.2.2 Quantitative methods

On the principle, quantitative methods are simple, as it aims to quantify the risk. Recalling the definition of risk (paragraph Definitions and concepts3.2), risk is the possibility of a loss to something of value. Hence, the correct way to quantify a risk is by showing a probability distribution affecting the value of interest. The value of interest can be binary, discrete or continuous:

- Binary example: chance of leakage: no = 99% ; yes = 1%
- Discrete example: number of accidents in 30 years: 0 = 75%; 1 = 15%; 2 = 5%; 3 = 2%; etc.
- Continuous example: quantity of CO_2 released from the storage complex in case of leakage, see Figure 3

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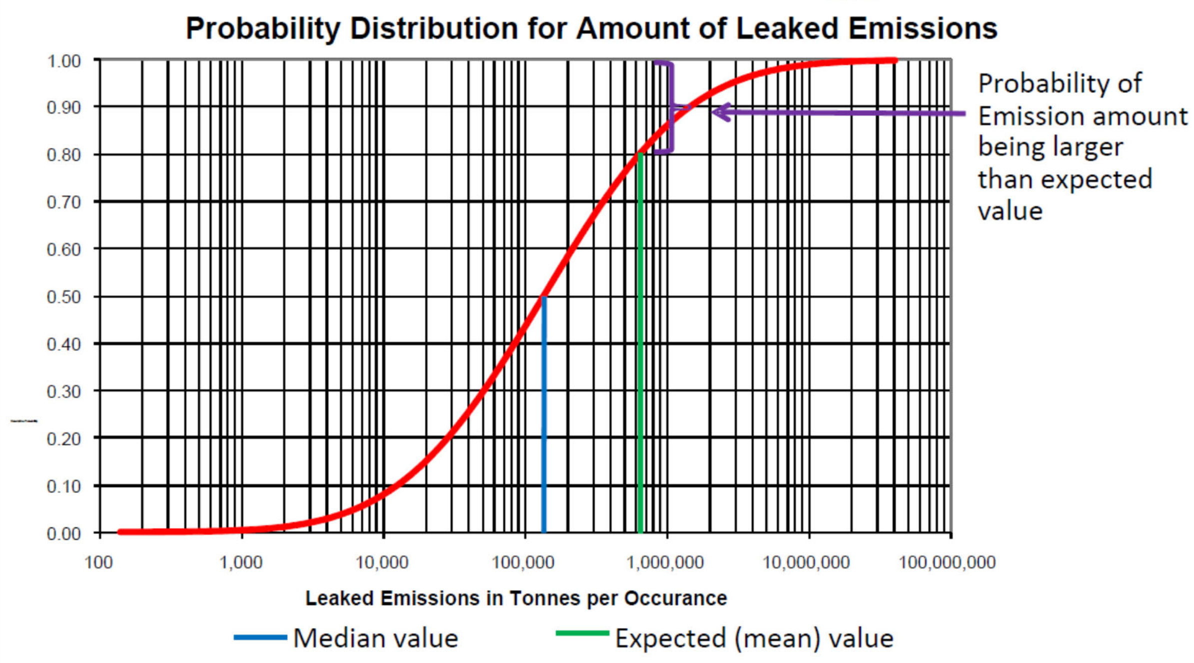

Figure 3: example of quantification of leakage risk (source: European Commission. Directorate General for Climate Action., 2011)

The main difficulty of quantitative methods is to be able to "find the numbers". Hubbard (2009)[2] have several advices in order to facilitate the use of quantitative methods. We only summarize the most important ones here.

The first important thing is that often, numbers must come from experts, particularly when there is little data (a situation that is expected early in a project). Hubbard (2009) defends a subjective view of the risk: there is no "correct" probability, as it is only a representation of our own uncertainty about reality. He provides many practical advice for "calibrating" experts: meaning that when they express a confidence of 90%, they should be correct 90% of the time (and more generally for any percentage).

The second important aspect is that probabilities can and should be decomposed, and modelled. It is not always easy to come with a number for a given risk scenario, but it is easier when one analyses first the risk factors, the potential causes, the needed combination, etc. He provides three maturity levels for models:

- Level 1, "better than qualitative": Just describe the basic behaviour of the system in terms of a distribution
- Level 2, "even better": List other factors that historically correlate with the event you are trying to model
- Level 3, "best": Build a structural model

We will present a method to build a structural model in section 6.2.

[2] There is a new version of the same book since 2021 but we have not read it so we refer to the earlier version

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4.3 Risk assessment in the CCS directive

4.3.1 CCUS directive

The directive on the geological storage of CO_2 (the "CCS directive")[3] establishes a legal framework for the environmentally safe geological storage of CO_2. Safety of the storage is a main concern as the directive clearly states: "A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist."

Annex I lays down the criteria for the characterisation and assessment of the potential storage complex and surrounding area. A required step is risk assessment, which shall comprise "hazard characterisation", "exposure assessment", "effects assessment", and "risk characterisation". These different phases, as described in the directive, broadly correspond to the risk identification / analysis / evaluation phases of the ISO 31000 described above. Built on the ISO 31000 norm, the PilotSTRATEGY methodology provides a comprehensive framework, which will encompass the directive's requirements.

Hazard characterization means essentially to compute the risk of leakage[4]. In particular, the directive requires considering the following aspects:

"(a) potential leakage pathways;

(b) potential magnitude of leakage events for identified leakage pathways (flux rates);

(c) critical parameters affecting potential leakage (for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s));

(d) secondary effects of storage of CO_2, including displaced formation fluids and new substances created by the storing of CO_2;

(e) any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project). "

Exposure assessment means to evaluate how likely a given leakage (or other hazard) may reach a vulnerable element (e.g. humans, plants, species, drinking water)

Effects assessment means to compute the potential impact of a possible leak on those vulnerable elements.

Risk characterization is essentially the integration of the previous steps, with analysis of the main sources of uncertainty in order to assess a "risk of leakage".

[3] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031
[4] The directive does not mention in the annex the risk of induced seismicity. This risk will be included in the PilotSTRATEGY method

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4.3.2 Guidance Document 1

To ensure the implementation of the CCS Directive, the European Commission also published a guidance document that outlines a CO_2 storage life cycle risk management framework (European Commission. Directorate General for Climate Action., 2011a).

The framework for risk management in geological storage is defined as follows:

"

- *Risk identification and assessment: Identify and characterise risks relating to potential leakage from the storage complex, other significant environmental or health risks and associated uncertainties; The identification and assessment of risks should involve hazard identification, and the assessment of potential impacts for each identified hazard (i.e. Exposure and Effects assessments as required in CCS Directive);*
- *Risk ranking: Rank and characterise the potential significance of each risk; rank in one of the following categories: Insignificant/significant;*
- *Risk management measures: Identify and assess risk management measures, including monitoring activities, preventive and corrective measures that may be implemented, or planned as contingency measures, in order to reduce risks or associated uncertainties, and assess the resulting risk/uncertainty reduction and risk ranking;*

"

The methodology developed in PilotSTRATEGY is consistent with this approach, despite some differences in vocabulary. The framework proposed in the guidance document is based on the CO2QUALSTORE guideline[5], but the authors specify that the operators can use their own risk management process, as long as they can demonstrate that it meets the requirements of the CCS Directive.

Just like in the PilotSTRATEGY approach, this framework starts with the risk identification step. The guidance document proposes generic risks/hazards for different options and leakage pathways, which can be used as checklists, divided into the following categories:

- Geological leakage pathways;
- Leakage pathways associated with manmade systems and features (i.e., wells and mining activities);
- Other hazards or risks such as the mobilisation of other gases and fluids by CO_2 (e.g. methane).

According to the risk ranking step, which would roughly correspond to the risk evaluation step of the ISO 31000, the guidelines recommend to "categorise and rank the identified risks based on a standard matrix of probability and severity of outcome (impacts)". This method will not be prescribed in PilotSTRATEGY, as the objective is to make quantitative risk assessment (see 4.2.1).

[5] DNV, 2010a, Det Norske Veritas (DNV), CO2QUALSTORE Report - Guideline for Selection, Characterization and Qualification of Sites and Projects for Geological Storage of CO2, 2010.

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Finally, the guidelines insist on the life-cycle risks: to consider the risk assessment at each stage of the project (selection, operation, closure…) and to constantly update it with data from previous phases.

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5. Description of the PilotSTRATEGY method

This chapter outlines the workflow designed in WP5 to carry out the safety and performance analyses in each region of PilotSTRATEGY. The method is based on the ISO 31000 norm for risk management (see 4.1) and the workflow below specifies its implementation in the framework of PilotSTRATEGY, in particular the needed interactions with the other WPs for a successful consistent risk assessment.

5.1 An iterative method

We propose a two-round approach: the workflow described below – from step 1 to step 3 - is carried out a first time in a "light" way; then, in a second round, with "heavier" work on events which would have appeared in the first round as requiring deepening for risk analysis. The use of quantitative methods from the beginning allow for better recommendations regarding where the effort should be in the second round, using methods such as sensitivity analysis.

5.2 First step – experimental design: explain what will be measured and how

A risks identification regarding the storage is performed in the most comprehensive way as possible: all possible events that can alter safety or performance of the storage are considered, together with all potential causes and consequences.

Different methods can be used for this purpose:

- To list the risk events, we can base on generic list and adapt it to the site taking into account its own particularities (e.g. off-shore specific risks). (see 6.1.1.1 and 6.1.1.3)
- To identify all related causes and consequences for each risk event, and potential interaction between the events, we can use fault trees, bow-tie diagrams or influence diagrams. Examples are provided in 6.1.1.1 and 6.1.1.2.

In order to carry out the risks analysis (see 4.1.3.2) an experimental design is drafted for all identified risk scenarios. This means explaining how the risk will be measured (e.g. what model to use) and who will perform the related work among the WPs and partners. For example, numerical dynamic models have to be developed in WP3, design options come from WP4, etc. Propositions for the experimental designs ("who", "what", "when") will be validated during technical workshops with partners from WP2, 3 and 4.

The experimental designs refers to:

- Assessment of design options (e.g. positions, types of wells, injection strategies)
- Monitoring options
- Preventive and corrective measures options
- Models needed to assess each events (i.e. statistical, analytical, numerical, etc.)
- And overview of uncertainties and sensitivity analyses

Another workshop will be organised in the second round, following the first results obtained with a "light" application of the workflow, to update the experimental design.

5.3 Second step – computation: measure the indicators

The computation step aims to assess probabilities / likelihoods and impacts related to the main events described in the previous step, according to the plan provided by the experimental design. Most numerical models will be developed in WP3. In WP5, we will base on the models and surrogates elaborated in the WP3, as well as on simple stochastic models, to simulate a wide range of events: dedicated to wells, induced seismicity, CO_2 plume, etc.

These simulations allow obtaining the risk probability functions of the global CO_2 storage system for each of the defined risk scenarios. We will rely on Monte Carlo analysis in order to explore both uncertainties in existing data and in the various design options.

Simpler and "lighter" models will be favoured for a first round in order to get quick results for Step 3. In a second round, "heavier" models will be used where necessary.

In some cases, particularly in the first round, a model might not be feasible or necessary and the quantification can be made with experts elicitation directly.

See section 6.2 for more details regarding the step.

5.4 Third step – decision analysis: what to do with the results

The decision analysis step aims to evaluate the risks scenarios for storage safety and performance and to propose the best design alternatives for the pilot (well location and design, monitoring techniques and set up, mitigation measures, etc.).

To do so, we propose to gather and integrate the results from the previous steps and related WPs (i.e. results of models from WP3, design options from WP4, results of WP5 simulations), and evaluate the design options using decision analysis tools such as cost-benefit analysis or multicriteria analysis. As in most decision problems, an important aspect here is to manage uncertainties. This will be done with recognized techniques such as sensitivity analyses.

For the first round, the goal is to understand which variables (data) and models are most sensitive with respect to the safety or performance objectives. We will use methods such as Value of Information (VOI) which aims at identifying where uncertainty reduction (e.g. by further data acquisition or refinement of models) is most effective. This will guide the second round and prioritize the new models (back to First step and Second step).

In the second round, the decision models are updated following the results of the "heavier" simulations. The updated evaluation provides the basis for the recommendations (see 5.6).

Propositions of tools and useful references for decision analysis are provided in section 6.3.

5.5 Stakeholder engagement process

The PilotSTRATEGY method also considers dialogue with stakeholders on the topic of safety and performance, in line with best practices regarding risk governance where risk studies are performed in good understanding with all types of actors. This will allow the project team to understand how

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the stakeholders view the risks and to refine the risk assessment with additional concerns raised by stakeholders.

In particular, we will seek their feedback on the on-going work carried out in the workflow described above in order to consider alternative options, other models, etc. and, reversely, to see how "risk assessment activities" can provide better answers to stakeholders.

These exchanges about risks perception will be conducted in the framework of Regional Stakeholders Committees meetings in close collaboration with WP6 partners. Risks will not be put forward at the first meetings, but related discussions should be recorded and see how they can influence the work in WP5.

5.6 Recommendations

Recommendations for safety and performance of the storage pilot are drawn based on the work performed in the previous tasks. These recommendations shall address the following categories:

a. Future (Post project) research (include data acquisition, new model, etc.)

b. Design / options recommendations

c. Draft monitoring plan

d. Draft corrective measure plan

e. Other legal and regulatory requirements (e.g. Environmental Impact Assessments

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6. Tools and examples

In this chapter, we provide some tools and examples that show how to apply the PilotSTRATEGY method in a more concrete manner. It is broadly organised following the steps of ISO31000.

6.1 Tools and examples for risk identification

Risk identification tools and methods depend on the objectives. We first describe tools and examples for safety risk identification, and then for other type of performance risk identification.

6.1.1 Safety risk identification

6.1.1.1 BRGM method and bowtie diagrams

For safety risk identification, BRGM has developed a method based on bow-tie diagrams (De Lary et al., 2015).

Bow-tie diagrams is a graphical method that display risk scenarios. Bow-tie diagrams have become a standard in the Oil & Gas industry and have been used in many recent CO_2 storage projects (Zweigel et al., 2021). On the principle, the diagrams present a central event, preceded by potential threats and followed by potential consequences. Barriers can be placed on the diagram to each side of the event (either to reduce its likelihood or the severity of the consequences) (*The Bowtie Method - CGE Barrier Based Risk Management Knowledge Base*, n.d.).

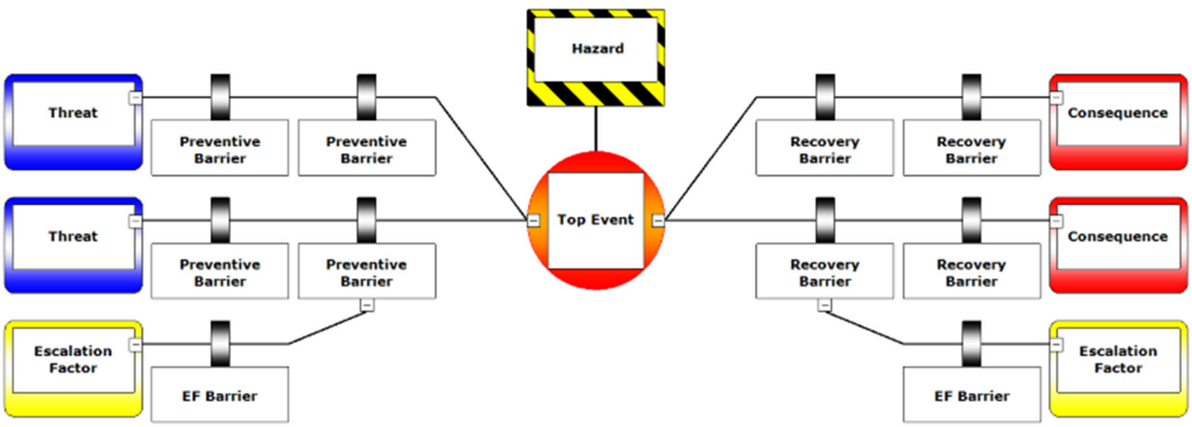

Figure 4: example of a bow-tie (from The Bowtie Method - CGE Barrier Based Risk Management Knowledge Base*, n.d.)*

The BRGM method was developed for several uses in the subsurface, including – but not restricted to – CO_2 geological storage. The idea of this method is to propose generic diagrams that are adapted to each situation. The central events of each diagrams are:

- Leakage or fluid communication through:
  - Wells (in operation or abandoned)
  - Caprock
  - Faults
  - Caverns
- Unexpected modification of pressure and/or flow in the exploited formation
- Unexpected mechanical disturbances

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- Unexpected chemical disturbances in the exploited formation
- Unexpected thermal disturbances in the exploited formation

Using these events as a basis, the aim is to build a set of new diagrams exploring the various causes and consequences of each event, and the combination between these events.

Example

In a hypothetical site considered for the storage pilot, there will be one injection well, and one observation well entering the formation. There are no other identified wells. There is uncertainty on the presence of a fault in the caprock. By considering the first family of event, we create the following central events adapted to our sites:

- Central event n°1: leakage through operation well
- Central event n°2: leakage through observation well
- Central event n°3: leakage through caprock
- Central event n°4: leakage through faults

Considering the first central event, we brainstorm on potential causes, including consequences from other events:

- Chemical degradation following exposure to CO_2 (combination with the "chemical" event)
- Fracture in casing because of pressure (combination with the "mechanical" event)
- Defect in the tubing (new cause identified in brainstorming)

Once we have a comprehensive set of causes, we can brainstorm on the consequences:

- Pollution of subsurface aquifer
- Blowout of the wellhead
- Etc

We need to repeat this exercise for all the identified central events. This is typically performed in workshops.

In PilotSTRATEGY we propose to create a first set of diagrams in reduced groups first (e.g. only the partners involved in WP5 for instance), and then discuss and adjust them with all partners (the experimental design workshops could be a good opportunity for this) as well as stakeholders (as part of WP6 consultations for instance).

Tools

There are several possibilities for designing the diagrams.

The easiest is to draw the diagrams in a simple drawing software, such as Powerpoint, Google Slides or Google Drawings. It only requires to draw boxes, arrows, and to add text. Most partners will have access to these tools at no additional cost. The learning curve is very quick. On the other hand, they have little/no features dedicated to risk identification.

For more advanced and professional usage, partners can use professional bowtie software such as BowtieXP[6] which is the standard in O&G company. The advantages are that the formatting is

[6] https://www.cgerisk.com/products/bowtiexp/

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probably easier and have a more professional look, many features will help in the process of risk identification. On the minus side, the product is not free and probably require a little training before users can be comfortable with it.

6.1.1.2 Inference diagrams

An alternative to Bow-tie diagrams are inference diagrams. Inference diagrams (sometimes also called causal diagrams, causal Bayesian networks, depending on authors) are diagrams showing causal influence between variables, and are also designed to show decisions and utilities. They will be described in more details in section 6.2 as they have a quantitative aspect. In this section related to risk identification, we only describe the qualitative aspect.

Bow-tie diagrams are a great way to display risk scenarios, but there can be limitations to how these scenarios can be combined, and to adjust the level of complexity. For instance, it is not straightforward to display that two independent causes are necessary in order to create an event, or the effect of cascading events (e.g. blowout in the well create mechanical damage in the reservoir).

Drawing the bowtie diagrams as influence diagram can overcome these limitations (Fenton & Neil, 2018). Figure 5 is an example of influence diagram for terrorist risk assessment. The uncertain variables are the blank ovals. Decision about security measures is displayed in a grey square. The grey diamond represent various utilities (i.e. something of value).

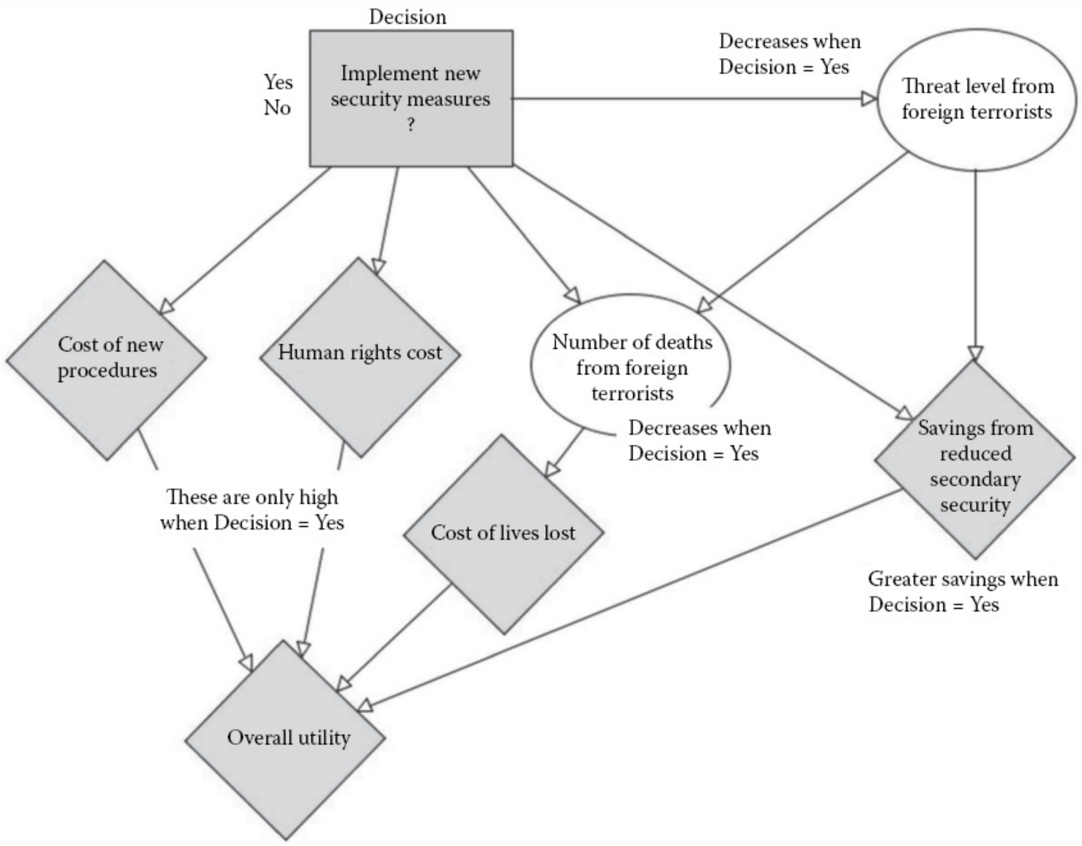

Figure 5: example of influence diagram for terrorist risk assessment (Fenton & Neil, 2018)

We can use the format of influence diagrams to draw bow-tie diagrams. Depending on the need, the resulting diagram can be very similar to a bowtie diagram, or constructed with additional features. The complexity can be adapted to the stakeholders.

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Tools

As for bowtie diagrams, a straightforward way to draw influence diagrams is to use a drawing software such as Powerpoint or Google Slides, but these will be limited to drawings and will not have the quantitative part which is necessary for risk analysis.

For integrating the quantitative part of influence diagrams, a first possibility is to use programming languages such as R or Python. In R, this will be done using a Bayesian network module (bnlearn) which has graphical capabilities[7]. In Python, a recent module was developed for creating and solving Causal Influence Diagrams (Fox et al., 2021). However, the graphing part is created through lines of code which is far from ideal in a brainstorming process. We recommend in this case to brainstorm about the diagram using a drawing software (see above) and then to switch to the programming language for the quantitative part.

From a user perspective, a better alternative is to use professional influence diagrams or Bayesian network software. Here are two examples worth considering:

- Agenarisk[8] which is promoted by the authors of Fenton & Neil (2018)
- Analytica[9] which was specifically developed for drawing and computing influence diagrams. There is a free version that allows to manipulate up to 100 variables.

The main advantage of these softwares is that they have drawing capacities for designing the diagram, and they can compute the diagram, which will be useful for the analysis step.

6.1.1.3 Features, Events and Processes

An often cited method for risk identification are Features, Events and Processes (FEPs) (Savage et al., 2004). Quintessa maintains a database of many FEPs dedicated to CO_2 storage[10]. It is a list – constructed to be as comprehensive as possible – regarding potential features, events and processes that can happen in the context of a CO_2 geological storage. One use is to assemble FEPs in order to construct different scenarios of evolution. However, the potential combinations are numerous and it can be tedious. BRGM recommends to use FEPs as an auditing tool: first constructing risk scenarios (for instance using BRGM method explained above), and then checking the list of FEPs to see if anything might be missing from the scenarios.

6.1.2 Performance risk identification

In the context of WP5, it is also possible to use risk management methods for risks other than safety, which we call "performance" risks.

The preliminary step is to be clear about the objectives of the project (besides safety). The two main performance objectives are:

- Storage performance: the goal is to store a certain amount of CO_2. As a climate change mitigation tool, both the total capacity and the possible injection rates are important

[7] https://www.bnlearn.com/
[8] https://www.agenarisk.com/
[9] https://lumina.com/
[10] https://www.quintessa.org/co2fepdb/v2.0.0/

- Economic performance: the goal for the operator and other financers is at least not to lose money on the long term. This can be expressed in many different economic indicators and can involve various sources of income.

Recalling that performance was defined in relation to the stakeholders' expectations, there are other performance objectives that can be defined, but they generally are variations around storage, economic and safety performance. In any case, it is necessary to consult with these stakeholders in order to be sure that at least one objective takes account of their expectations.

Once the performance objectives are clearly defined, performance risk identification consists in designing scenarios that would prevent these objectives from being met. In order to do this, the same techniques presented for safety risk identification can be applied, in addition to other techniques as necessary:

- The BRGM central event can still be relevant for subsurface processes
- The Quintessa FEPS can also be used as prompts for building adverse scenarios

Amongst the standard techniques for risk identification we can mention:

- Taking account of historical data, near misses etc.
- Review of internal and external factors
- What if? Scenario analysis: this method consider that what could go wrong is going wrong, and the team needs to find the reasons why it did.
- Any other brainstorming method: we mention here the "whole story framework" which forces to consider the situation from different perspectives in order to think of more risks (Hnottavange-Telleen, 2018)

Example

For a hypothetical storage site, we want to ensure to have enough injectivity. We would consider 500kt/year as a minimum.

Reviewing BRGM central events and the list of FEPs, the team creates these first scenarios:

- Poor drilling and completion method leads to a high skin effect in the well
- Precipitation effect around the wellbore which impedes flow
- Undetected "flow barriers" in the reservoir
- Low average permeability

6.2 Tools and examples for risk analysis

In this part we expand on the method presented in paragraph 4.2.2 on the quantitative methods, which are the methods favoured for PilotSTRATEGY.

We focus on the level 3 proposed by Hubbard (2009) (section 4.2.2) which consists in building a structural model of the risk. The idea at this stage is to model how the risk could materialize, and to use all relevant variables, as well as the uncertainty for each of those variables. Then, risk is computed with Monte Carlo simulations: a computer program simulates a large number of alternate universes which represent one possible realization of the model. For each realization, the value of

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each variable is assigned randomly by the computer following the "logic" of the model. See the examples below.

In practice, building a risk model is composed of two main parts: 1/ the structure and 2/ the numbers:

The first part is to draw the structure of the model. Here, it is necessary to list the relevant variables which will influence the risk, as well as the relationships between these variables. One common advice is to start "small" with something that works: it is better to add complexity to a simple model that works than to try to fix a complex model that does not work.

The second part consists is assigning numbers to each variables, and describe the nature of the relationships between these variables. For example the value of some variables can be functions of other variables. There are three main sources of "numbers" for this part:

- Data: if there exists recordings or observations about a certain variables, then these observations can be directly fed into the model. Example: measurements of permeability.
- Models: when a direct measurement is not available, the variables can be computed using a model. For instance, the distance of the CO_2 plume can be computed with numerical models under some hypotheses.
- Experts: when no data or model is available, then experts of the subject can provide an educated guess regarding the values of the variables. An important topic is the calibration of experts: an expert is said to be calibrated when his or her assessed chance of being correct corresponds to the actual percent correct. This is measured using calibration tests for instance by answering trivial question and providing confidence percentages. Most experts are overconfident, which has the effect of underestimating the risk. This can be corrected by training (D. W. Hubbard, 2009).

Calibration of experts is a bit out of the PilotSTRATEGY scope, and the reader can check the book by Hubbard (2009). There are ways to overcome biases by eliciting independently (i.e. experts should not be influenced by other answers) several experts, and to record their assessments in a database. These assessments should be treated as other types of data. Depending on the needs of the project, a task of WP5 could be dedicated to providing a method for aggregating expert elicitations.

The three sources of inputs are generally combined when building a model. This combination is often done intuitively, for example the experts provide numbers after checking relevant data and models. There are more formal ways of combining different inputs, for instance using Bayesian statistics.

In our experience, both part (structural and quantitative) are equally challenging, but adopting a phased approach (i.e. starting with simpler models and gradually increasing complexity) greatly facilitates the whole process.

It is also worth mentioning that not one model is 100% correct, and it is thus possible to build more than one model (e.g. a simple one and a more complex) and to compare the results.

Tools

Influence diagrams and causal Bayesian networks are a natural way to build such model as they provide two essential features for such models:

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1. The ability to have different variables which are dependent on each other
2. The ability to handle uncertainty in the quantification of the variables

In addition to influence diagrams, it is also possible to use:

- Spreadsheet: this solution is often the easiest to most people, but there is a need to handle uncertainties properly in spreadsheet, mainly with Monte Carlo simulations;
- Statistical programming: with languages such as R or Python, they have modules designed for complex Monte Carlo simulations. They can handle more complexity than spreadsheet but will be harder for users less experienced with such languages.

Example

We focus here on the risk of blow-out of the injection well as an example.

Level 1: for the first round, it will be enough to produce a rough guess of this risk, based primarily on expert judgment. For instance, the probability of a blowout during the lifetime of the site can be 1%. Regarding impact, we quantify this with a quantity of CO_2 released. We can provide a 90% interval estimate: the expert think there is a 5% probability that the quantity released is less than 1 ton of CO_2 and a 95% probability that it is less than 10 000 ton of CO_2. A loss exceedance curve can be drawn using a Monte Carlo simulation in Excel:

1. We model the probability of a blowout using the *RAND()* function (which produces a random number between 0 and 1, uniformly distributed), and comparing the result with the likelihood (1%): if the result of *RAND()* is inferior to 1%, then it is true (value of 1 in Boolean), else it is false (value of 0). We repeat this operation a 1000 times.
2. We infer the parameters of the lognormal distributions from the provided percentiles. Taking the natural logarithm of these percentiles, we can first infer the parameters of the corresponding normal distributions. This is done using the quantile function[11].
3. We can now compute a thousand realization of the loss function using the inverse lognormal function in excel, and another *RAND()* as parameter.
4. We multiply both distributions to get the result
5. Based on the series of numbers obtained, we can draw a loss exceedance curve, which is a reverse cumulative function

The result is displayed on Figure 6.

[11] https://en.wikipedia.org/wiki/Normal_distribution#Quantile_function

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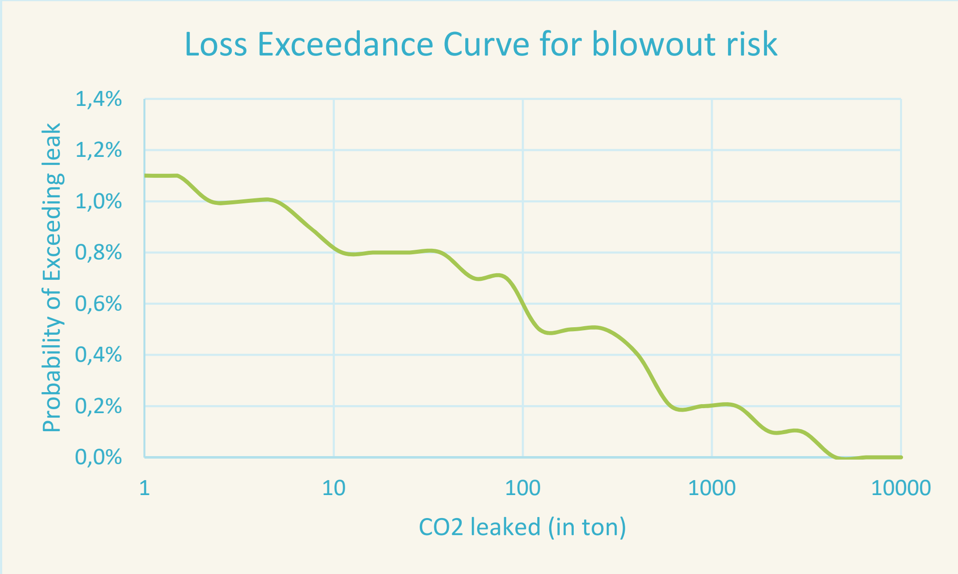

Figure 6: Example of a loss exceedance curve for blowout risk

Level 3: for the second round, there is a lot more data available, a design of the well is available and so a model representing cause-effect relationship can be created. We can represent the chain of events with a Bayesian network (BN).

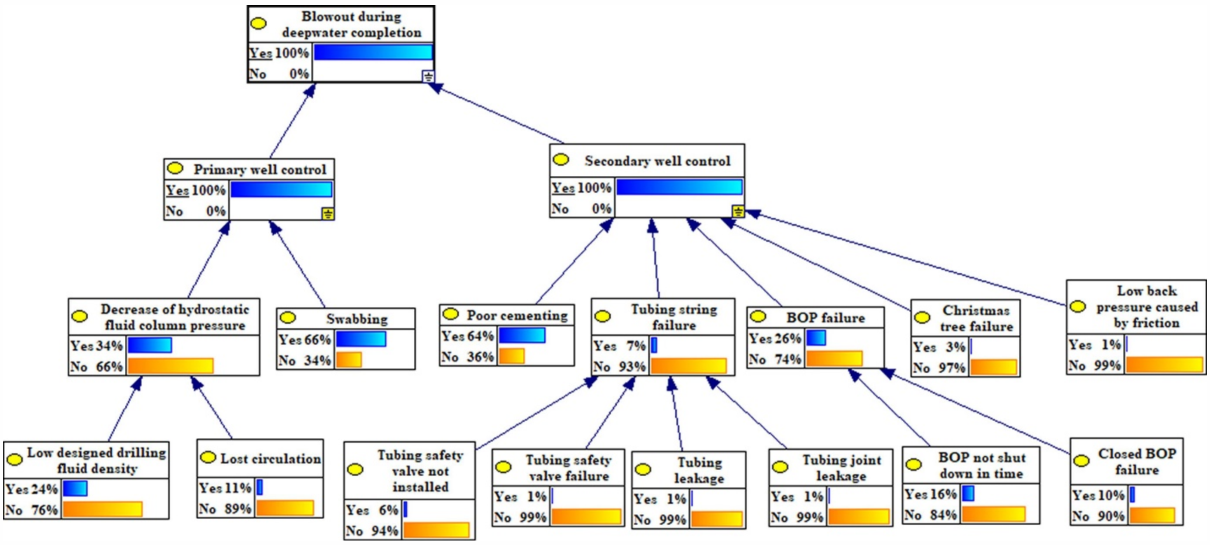

Figure 7: example of a Bayesian network representing blowout risk (Yin et al., 2021)

Figure 7 shows an example of a Bayesian network (BN) for blowout risk: each individual node represents a component of the well, and it shows the associated probability of failure. The strength of BN is that it automatically computes the overall risk of blowout by combining the individual risk of failures.

6.3 Tools and examples for decision analysis

In the context of PilotSTRATEGY, decision analysis is used for two aspects:

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- In the first round, we can use Value of Information (VOI) to highlight the source of uncertainties which have the greatest influence on the decision
- In the second round, decision analysis can be used to make recommendations regarding design of the pilot, monitoring plan and corrective measures plan

The pre-requisite is to have a quantitative decision model, showing how a particular choice will perform under the hypotheses of the model.

For instance, in the blowout example, we could compare the risk with two alternate completions (which would have different costs) and see how the risk differs between these two options. Decision analysis can then be used to propose a decision, based on a robust ordering of the alternatives, considering preferences regarding risks and costs. More information on decision analysis tools and practices can be found in Edwards et al., (2007).

For an introduction to VOI methods, the reader can check Bratvold et al. (2009). Trainor-Guitton et al. (2013, 2014) show applications of VOI in the context of CO_2 storage and geothermal exploration respectively.

For decision analysis, the same tools apply than for risk analysis:

- Spreadsheet can be used but have limitations
- Programming languages such as R and Python are the most versatile but require dedicated development
- Dedicated software such as Analytica or AgenaRisk may be a good compromise but are commercial software (i.e. not free).

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7. Conclusion and perspectives

This report provides resources to guide the work of WP5 of PilotSTRATEGY on safety and performance. The proposed method relies on existing methods and principles and primarily ISO31000 on risk management and the CCS directive. However, an effort is made in PilotSTRATEGY to use quantitative risk assessment and decision analysis as much as possible. It is in line with an overall objective of PilotSTRATEGY to use best practices during the whole characterization process.

The PilotSTRATEGY method for safety and performance risk management is described and tools and example are provided for more guidance.

The next step is to start to implement the method on the case studies. In applying the principles explained in this report, the teams may find some difficulties in some aspects of the method. It will be the opportunity to review and adjust part of the methods. Some focused methodological developments can help in streamlining the whole process. Early discussion and feedbacks with the authors is thus highly encouraged.

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