MiReCOL Mitigation and Remediation of CO_2 Leakage

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Submitted (Author(s))	Rajesh Govindan et al.	April 2017
Verified (WP-leader)	Anna Korre	6 April 2017
Approved (SP-leader)	Anna Korre	6 April 2017

Author(s)		
Name	**Organisation**	**E-mail**
Rajesh Govindan	Imperial College	r.govindan07@imperial.ac.uk
Zhenggang Nie	Imperial College	zhenggang.nie04@imperial.ac.uk
Anna Korre	Imperial College	a.korre@imperial.ac.uk
Sevket Durucan	Imperial College	s.durucan@imperial.ac.uk

Public abstract

The objective of the task presented in this deliverable report is to synthesise the results of the modelling studies carried out in SP1, SP2 and SP3, focusing on various mitigation and remediation techniques, and carrying out an evaluation of their performance as either threat barriers (for risk reduction) or recovery and preparedness measures (for consequence benefits) that can be achieved. The issues considered were relating to technology specific issues of the techniques, including their implementation costs.

A methodology is proposed to develop an effective framework which allows for the optimal allocation of resources for remediation technology implementation, considering the uncertainty with regards to their outcome, *i.e*. success or failure. It benefits from the assessment of the remediation techniques that was previously carried out based on five performance metrics, namely: (a) likelihood of success; (b) spatial extent; (c) longevity; (d) response speed; and (e) cost efficiency. Thus, the specific objective of the work presented in this deliverable report is to assimilate these metrics in the design of a protocol for optimising the selection of a subset of remediation techniques, representing the desirable remediation portfolio under uncertainty, in terms of the expected values of their implementation costs.

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1 INTRODUCTION

1.1 Objective

The overall objective of WP11 is to synthesise the results of modelling studies carried out under the scope of the MiReCOL project. The bow-tie analysis was used to facilitate the assessment of broadly two groups of techniques that were investigated in the project (see Figure 1):

- threat barriers, referred to as risk mitigation techniques, for recovery and preparedness; and
- consequence barriers, referred to as remediation techniques, in order to reduce the severity of the consequences.

The assessment involved the performance characterisation of remediation techniques that address a broad range of consequences owing to CO_2 leakage, including the loss of storage permanence, effects on the complex structural integrity, and possible interference with production or other storage licenses. A standardised ranking system based on technology-specific performance metrics, *viz.* the likelihood of success, spatial extent, longevity, response speed, and cost efficiency, was implemented.

However, it is recognised that the assessment lacks value for consequence reduction, unless it is complemented with an effective framework which allows for the optimal allocation of resources for remediation technology implementation, considering the uncertainty with regards to their outcome, *i.e.* success or failure. Thus, the specific objective of the work presented in this deliverable report is to design a protocol for optimising the selection of a subset of remediation techniques, representing the desirable remediation portfolio under uncertainty, in terms of the expected values of their implementation costs.

1.2 Optimal remediation portfolio

In order to achieve the aforementioned objective of remediation portfolio optimisation, a methodology was developed based on the concept of *decision trees*, which are probabilistic models for structured decision making comprising of a sequence of one or more decisions and their respective possible outcomes, characterised by probability distributions, with the aim of maximising/minimising the expected value of a user-defined utility/cost function (Fraser and Jewkes, 2013).

Thus, it provides a mechanism to decompose the large and complex problem of defining a remediation portfolio into smaller decision making steps by selecting from a range of techniques with variable success likelihoods, as presented previously in MiReCOL deliverable D11.2 and briefly discussed in the following section. In addition, the decision tree was designed in a manner which allows user customisation. In other words, depending on the circumstances, such as the site-specific conditions and leakage severity, users have the flexibility to prioritise amongst the performance metrics over time. Thus, the expected value of the implementation costs incurred in a given portfolio was determined, and the one which minimises the cost function for consequence reduction, considering the uncertainty in the success of its implementation, was flagged as the optimal portfolio.

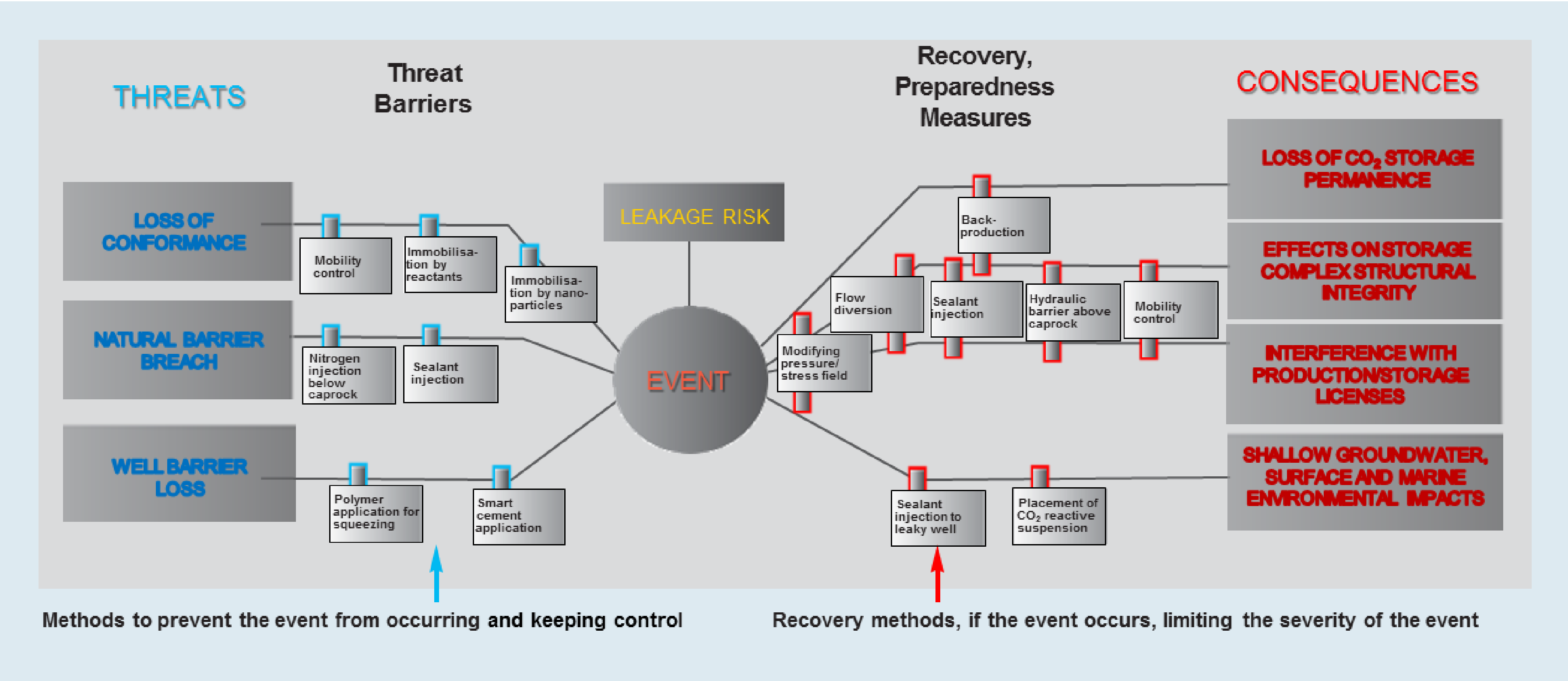


Figure 1. The bow-tie diagram for the MiReCOL project.

2 CO_2 LEAKAGE REMEDIATION TECHNIQUES AND PERFORMANCE ASSESSMENT

2.1 Remediation techniques investigated in the project

2.1.1 Flow diversion of CO_2 plume using foam injection

Foam is used in the oil and gas industry for mobility control of gas sweep during enhanced oil recovery. The desired effect is to reduce the mobility of the gas, forcing the injected gas to take alternative paths thus contacting more oil as well as delaying gas breakthrough in the production wells. Foam is also used to reduce gas coning/cresting at production wells.

In the current context, foam injection was investigated by SINTEF as a technique to remediate CO_2 leakage, in the event of an unexpected migration of the plume in the reservoir. It primarily involves the injection of a solution comprising of surfactant and brine in the reservoir. The solution reacts with the CO_2 in-place leading to the generation of foam, which causes the reduction in the mobility of the CO_2, thereby minimising potential leakage. The plugging effect of foam treatment depends on several factors, including the reservoir geology, position and type of leakage, injected surfactant volumes, surfactant concentration, adsorption, foam strength and foam stability. The main purpose of the study was to explore the ranges of some of these factors and to quantify their impact on a leakage event. The results obtained were discussed in detail in deliverable D3.3.

2.1.2 Flow diversion of CO_2 using polymer-based gel injection

Cross-linked hydrolysed polymer-gel injection is used in petroleum industry to improve conformity of fluid flow in the reservoir, remediate leakage around wells, and also used in conjunction with enhanced oil recovery at various temperature and pressure conditions. Water-based gels are highly elastic semi-solids with high water content, trapped in the three-dimensional polymer structure of the gel. Polyacrylamide (PAM) is the main cross-linked polymer used mostly by the industry. The use of biopolymers is more challenging as compared to the synthetic polymers due to chemical degradation at higher temperatures, causing the loss of mechanical strength. Most of polymer-gel systems are based on crosslinking of polymers with a heavy metal ion. The most commonly used heavy metal ion is chromium III. However, in view of its toxicity and related environmental concerns, its application in reservoir conformance and CO_2 leakage remediation is considered to be limited. Therefore, more environmental friendly crosslinkers such as boron, aluminium and zirconium have been proposed and used in recent years.

Imperial College used numerical simulators to implement the known interaction properties of polymer solution and crosslinkers using data from the literature and laboratory tests. The effect of reservoir permeability, polymer and crosslinker concentrations, pH and gelation kinetics were investigated. The property-based results were further translated into the simulation of scenarios for CO_2 leakage remediation using polymer-gel injection in the reservoir. The results obtained were discussed in detail in deliverable D6.3.

2.1.3 Flow diversion of CO_2 using brine/water injection

In secondary oil recovery, brine or water injection has a long history either to support reservoir pressure or to displace oil towards producing wells. There is a range of techniques and theories (*e.g.* Buckley Leverett analysis) about how water injection can be used to increase oil recovery. Volumetric sweep management and realignment of production in contiguous layers are the nearest analogues in the oil industry to the use water injection in order to stop the migration of CO_2. Industry has studied several mechanisms by which water injection can be used to reduce CO_2 migration, such as: (1) creating a high-pressure barrier in front of the migrating CO_2 plume; (2) chasing CO_2 with brine ensuring storage security; and (3) injecting water directly into the advancing CO_2 plume.

Three different examples of water injection remediation have been investigated by the project partners, listed as follows:

- SINTEF used a portion of the Johansen formation as the basic model with water injection in front of the CO_2 migration plume. The model was modified to represent the key characteristics of twenty other possible CO_2 storage aquifers.
- Using a generic model, Imperial College studied the reduction of CO_2 leakage through a sub-seismic fault by means of water injection via the well previously used for CO_2 injection.
- TNO also used the Johansen model to simulate ten alternative scenarios using a combined approach of water injection and CO_2 back-production as remediation measures.

The results obtained were discussed in detail in deliverable D3.4.

2.1.4 Flow diversion of CO_2 using brine/water withdrawal

The over-pressurisation of the reservoir during CO_2 injection is of concern because it could have a large-scale impact, namely interference with the operations in neighbouring oil and gas fields, or CO_2 storage sites that could co-exist in the same formation. Such interference also has regulatory implications since issuing permits to operators would then be based on the outcome of a multi-site process evaluation, which can be quite involved, and rather unnecessary. In the literature, it was demonstrated that by producing brine from the reservoir, the pressure-driven leakage was minimised and consequently the net of amount of leakage is largely buoyancy-driven, thus reducing the rate of leakage. While pressure management via brine extraction is not be considered a mandatory component for large-scale CO_2 storage projects, it could also potentially provide many other benefits, such as increased storage capacity utilisation, simplified permitting, smaller area of review for site monitoring, and the manipulation of CO_2 plume in order to increase its sweep efficiency.

Imperial College investigated the technique using numerical simulations of CO_2 storage and leakage remediation for an offshore and compartmentalised depleted gas reservoir, called the P18-A block (in the Dutch offshore region). The scenarios considered the study of a cluster of gas fields in the reservoir to understand the plume migration and reservoir pressure response during CO_2 injection, and the remediation achieved using brine withdrawal in terms of flow diversion and pressure relief. The results obtained were discussed in detail in deliverable D4.4.

2.1.5 Blocking of CO_2 movement by immobilisation of CO_2 in solid reaction products

Experience with unintentional precipitation or scaling and formation damage, as commonly encountered in the oil and gas or geothermal industries, sheds some light onto the possibilities for forming solid reactants. Minerals observed to form 'naturally' within the reservoir may all be potential candidates for controlled precipitation. Frequently occurring scales associated with oil and gas production are calcite, anhydrite, barite, celestite, gypsum, iron sulphide and halite. Re-injection of production water is prone to scaling of calcium carbonate, while strontium, barium and calcium sulphates are more relevant for seawater injection. In addition to fluid-fluid reactions, fluid-gas interaction could promote mineralisation. Controlled intentional clogging due to salt precipitation, which occurs when the solubility is exceeded by the evaporation into injected dry gas, could potentially prevent the leakage of CO_2. This process is similar to salt scaling in natural gas and oil production, and CO_2 injection in saline aquifers and depleted gas fields.

TNO investigated scenarios to study the feasibility of injecting a lime-saturated solution as a CO_2-reactive solution above the caprock, at the location where the leakage has been detected. The solution has a low viscosity which simplifies the injection process. The results derived for the injection of the lime-saturated solution provided a general insight in leakage remediation using non-swelling CO_2 reactive substances. However, the production and practical use of such a fluid was beyond the scope of the study. The results obtained were discussed in detail in deliverable D3.5.

2.1.6 CO_2 back-production

The back-production of formerly injected CO_2 may provide a suitable technique to: (1) mitigate undesired migration of CO_2 in the reservoir by inducing a pressure-gradient driven directed flow of CO_2; and (2) manage the reservoir pressure. Furthermore, the production of CO_2 will also form an integral part of any temporary storage of CO_2 in the frame of a different carbon capture storage and utilisation and/or power-to-gas concepts. In CO_2 storage combined with enhanced hydrocarbon recovery, CO_2 will be co-produced with the recovered hydrocarbons. The production ratio of gas to reservoir fluid is an important design parameter in all contexts. Below a minimum flow velocity in a well, the critical Turner velocity, no fluid is produced, and hence well load up (cone shaped brine accumulation) occurs.

The CO_2 back-production technique was investigated in this project using case studies based on two examples, each an offshore and onshore site, listed as follows:

- GFZ and Imperial College jointly carried out numerical studies prior to and after the Ketzin pilot field test to support its design and demonstrate the performance of the history-matched backproduction model, and thereby estimate the expected reduction in reservoir pressure achieved.

- TNO carried out a case study for the K12-B gas field in the North Sea to investigate the back-production technique. Numerical analyses focused on key factors such as recovery rate, CO_2 ratio, well pressure and water co-production.

The results obtained were discussed in detail in deliverable D4.3.

2.1.7 Hydraulic barrier

It has been suggested that injection of brine above the caprock, at a higher pressure than the CO_2 pressure in the reservoir, would create an inverse pressure gradient to reverse the flow direction and increase the solubility of CO_2 in the saline water barrier formed, and prevent or limit leakage. Furthermore, coupled with fluid management procedures during aquifer storage (saline water extraction and re-injection above the caprock), this can also be used to minimise displacement and migration of native brine, and avoid pressure build up in closed or semi-closed structures.

Imperial College investigated the effectiveness of pressure gradient reversal (PGR), a hydraulic barrier technique, as a potential remediation technique for CO_2 leakage from deep saline aquifers using a generic and geologically realistic model, comprising of the reservoir, caprock and an overlying shallow aquifer. The focus was on the role of controlling parameters which may affect the success or failure of the hydraulic barrier technology considered. The results obtained were discussed in detail in deliverable D7.3.

2.1.8 Polymer-gel-based sealant injection for well leakage remediation

The use of synthetic and biopolymer solutions by the petroleum industry has been mostly associated with enhanced oil recovery and widely used around the world. For polymer-gel compounds (usually crosslinked with a heavy metal), the application is considered for water-cut and flow conformance control within the reservoir as well as leakage remediation in the near wellbore area. The polymer solution is composed of molecular chains of the chosen polymer, a carrier fluid such as water or brine, and a crosslinker such as chromium III, zirconium, and aluminium. Polymers are made of coiled chains, especially of high molecular weight polymers. Once they are added into solution, the charged areas on the chain repel each other and force the chain to uncoil. As a result, the viscosity of the solution increases. Generally, the charge also affects the speed at which the chain uncoils. The higher charged polymers will uncoil faster, whereas, non-ionic polymers may never fully uncoil since they carry no charge.

Imperial College carried out both laboratory tests and numerical simulations to understand the effectiveness of polymer-gel treatment on the permeability reduction of wellbore cement, thereby effectively minimising CO_2 leakage through a microannulus between cement and casing interface, and in near wellbore region of the host/caprock. Specifically, deep, high temperature and high pressure reservoir conditions were considered for the simulations. The results obtained were discussed in detail in deliverable D9.3.

2.1.9 Polymer-gel-based sealant injection for caprock leakage remediation

Additionally, numerical simulations for polymer-gel injection above the caprock (in an assumed shallow aquifer) to seal fractures was also carried out by Imperial College. The results obtained were discussed in detail in deliverable D6.3.

2.2 Ranking of remediation techniques

The ranking of the remediation techniques was implemented using an ordinal classification - Low (L), Medium (M), and High (H) - based on the five performance metrics after pooling the results obtained from the leakage remediation simulation studies for each of the techniques (see Tables 1 - 5).

Despite being a qualitative ranking procedure, it represents the best efforts that could possibly be made to standardise the scales for the different metrics in order to ensure that the ranking is indicative of the overall merit of a given technique, and also allows for making a useful comparison between techniques. The rankings obtained were previously presented as success probability plots and spider chart visualisations in deliverable D11.2, and are summarised here in Table 6.

Table 1. Classification of the likelihood of success.

Rank	Likelihood of Success (%)
L	0 - 33
M	34 - 66
H	67 - 100

Table 2. Classification of the spatial extent.

Rank	Spatial Extent (km^2)
L	0 - 1
M	1 - 5
H	> 5

Table 3. Classification of the longevity.

Rank	Longevity (years)
L	0 - 1
M	1 - 10
H	>10

Table 4. Classification of the response speed.

Rank	Response Speed (years)
L	>1
M	0.1 - 1
H	0 - 0.1

Table 5. Classification of the cost efficiency.

Rank	Cost Efficiency (M€)
L	> 10
M	1 – 10
H	0 – 1

Table 6. Qualitative ranking of remediation techniques.

#	Technique	Performance Characterisation Metrics				
		Likelihood of Success	Spatial Extent	Longevity	Response Speed	Cost Effectiveness
1	Foam injection	L	L	M	H	M
2	Polymer-based gel injection	H	M	L	H	L
3	Brine/water injection	M	M	M	M	H
4	Brine/water withdrawal	H	H	H	L	M
5	Solid reaction products	H	L	H	H	M
6	CO_2 backproduction	H	H	M	L	M
7	Hydraulic barrier	H	L	M	M	H
8	Polymer-based sealant for well leakage	H	L	L	H	H
9	Polymer-based sealant for caprock leakage	H	L	L	H	H

3 METHODOLOGY FOR REMEDIATION PORTFOLIO OPTIMISATION

3.1 Remediation portfolio design and development

The design of the remediation portfolio was carried out inline with the principles of modelling and evaluation of decision trees. Three types of nodes were initially identified to model the portfolio, *viz.* (a) the decision node (D), which represents a point in time when the CO_2 storage site operator is obliged to make a choice from a given set of remediation techniques on the basis of his/her preferences (weights) for the performance metrics; (b) the chance node (S), associated with a random outcome which is anticipated by the operator as being either ‘success’ or ‘failure’ of implementation, and typically characterised by a Bernoulli distribution; and (c) the leaf node/endpoint (C), which represents a point where the cost function for an outcome of the terminal decision taken is indicated.

Figure 2 illustrates the basic structure of the decision tree developed for the purpose of remediation portfolio optimisation. The timeline for decision-making begins when leakage from the storage complex is detected (at T=0). The length of an individual decision time-step ideally depends on the outcome of the operator’s choice, *i.e.* if the selected technique is successful, its longevity would define the length of the time-step. It is also assumed that, in practise, a failed outcome would require the operator to take a new decision within one year since the last choice was made.

The methodology for remediation portfolio optimisation broadly comprises two steps:

- *Enumeration*: The exhaustive listing of alternatives in the decision tree is based on the preference/weighting for the five performance metrics over time. It is envisaged that at the time when leakage is detected, emphasis would be aptly placed on those techniques that have a relatively higher likelihood of success and a response speed, in order to enable the operator to take control of the situation. As time progresses, the weightings are allowed to become flexible and adaptive, depending on the site-specific conditions and leakage severity. However, the dynamic enumeration often leads to a complex decision tree and would need to be executed programmatically.
- *Backward Induction*: Following the enumeration of the decision tree, the computational task of remediation portfolio optimisation, *i.e.* the minimisation of the cost function for consequence reduction, was solved using a straightforward tree-traversal algorithm, which is an instance of an approach called backward induction in the game-theoretic and economic literature (Koller and Friedman, 2009). The algorithm proceeds backwards from the leaf nodes to the root node (the decision node at T=0) of the decision tree. The expected value of the cost function was computed at the beginning of every time-step when multiple choices are available for decision-making, subject to the operator’s weightings, as described previously. Thus, the decision node takes on the choice which corresponds to the minimum expected value of the cost function, thereby indicating the optimal remediation portfolio.

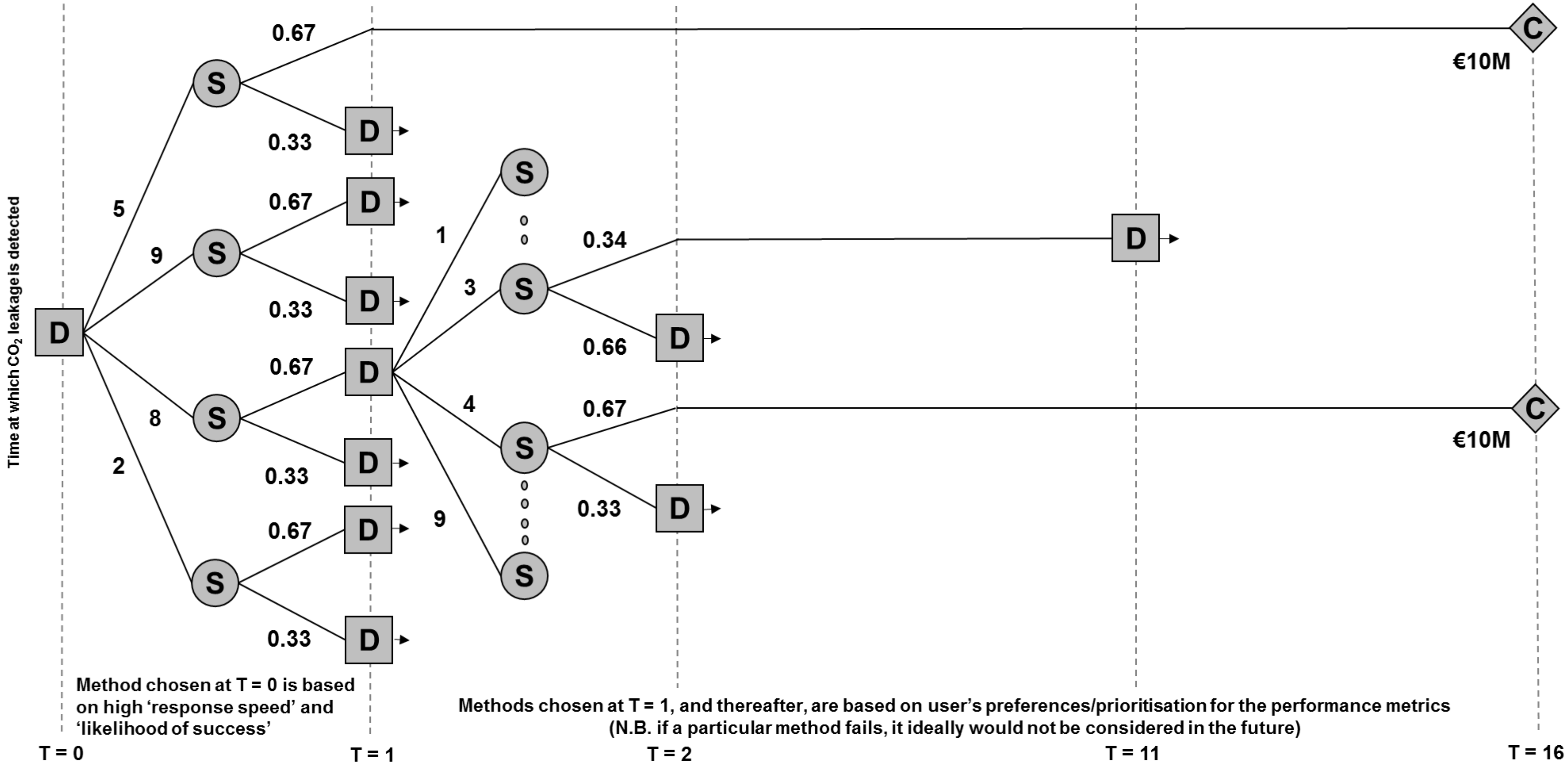


Figure 2. The decision tree structure for remediation portfolio optimisation.

3.2 Examples of remediation portfolio scenario optimisation

Two distinct scenarios were analysed in order to reflect the different operational constraints that apply to remediation options when leakage is detected during the injection period, or otherwise during the period after CO_2 injection has ceased.

3.2.1 Remediation of leakage detected during the injection period

One of the scenarios assumed in the study is the remediation of CO_2 leakage from the storage complex during the injection period. In this case, the operator would initially prioritise the implementation of those techniques that have a relatively higher likelihood of success and response speed, corresponding to decision node D_1, by assigning an equal weightage to these performance metrics. As a result, either of the techniques labelled 2, 5 or 9 (see Table 6) would be selected. Once the leakage situation is brought under control, it was assumed that the subsequent decision node D_2 would be based on the preference for techniques, labelled 4 and 6 (see Table 6), that have a relatively higher likelihood of success, spatial extent and longevity. The additional rules that were followed for the purpose of enumeration of the decision tree are as follows:

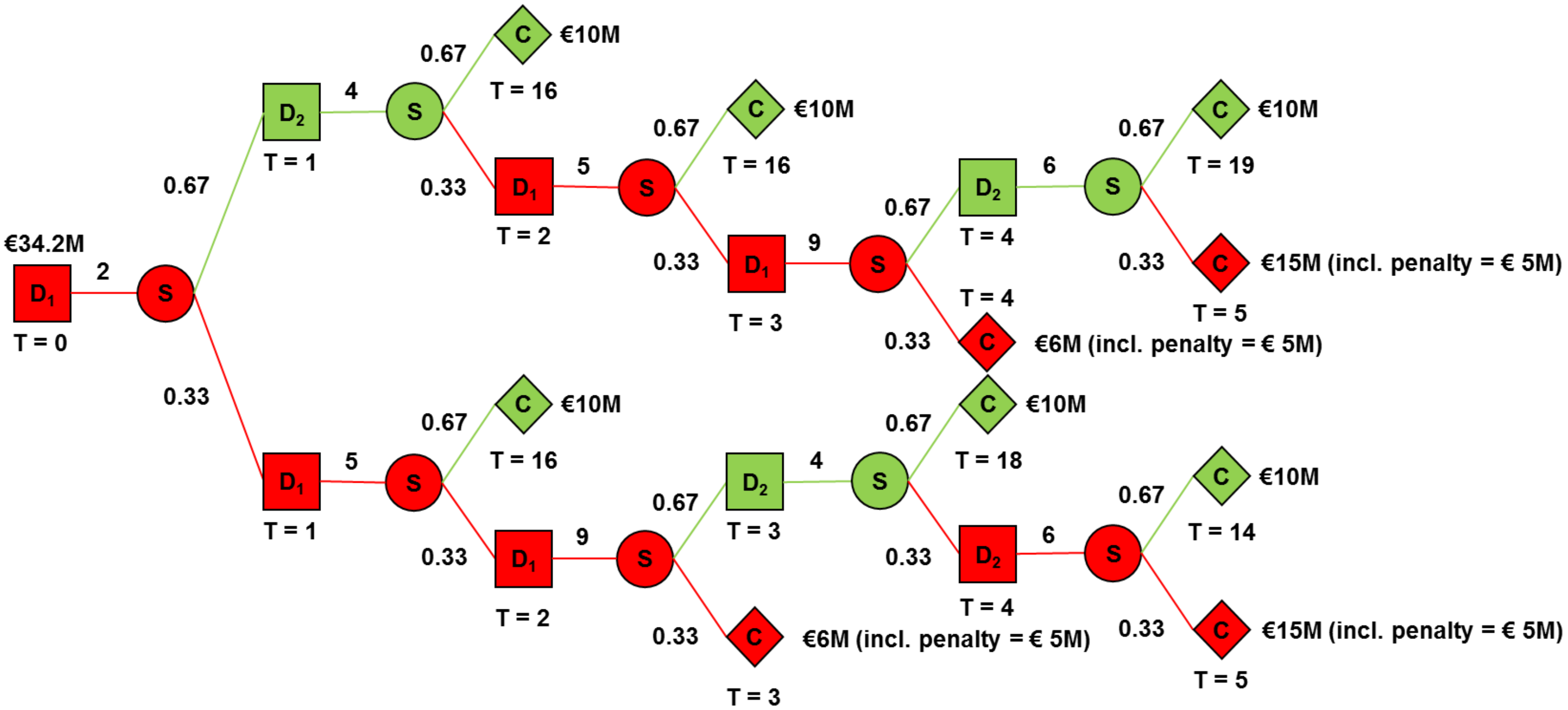
- If a particular method fails at either of the decision nodes, D_1 or D_2, other equally performing options would be tested; the failed method, however, will not be re-used for subsequent decision-making;
- For the purpose of visualisation, all the nodes in the decision tree and the connecting edges are colour-coded - green if it indicates a successful pathway, and red otherwise;
- The costs indicated at the leaf nodes would include an assumed penalty of €5M, in addition to the cost of the technique implemented, if it corresponds to a pathway which is colour-coded as red; the red leaf nodes represent the stopping condition where all the preferred options have been exhausted, and hence the attempt for remediation has failed;
- The remediation portfolios would span up to a maximum of 20 years.

Figures 3 and 4 illustrate two possible examples of remediation portfolios, starting with the injection of polymer-gel for flow diversion in the reservoir and solid reaction products respectively. Using backward induction, the expected value of aggregate costs incurred by the operator are €34.2M and €20.9M.

3.2.2 Remediation of leakage detected during the post-injection period

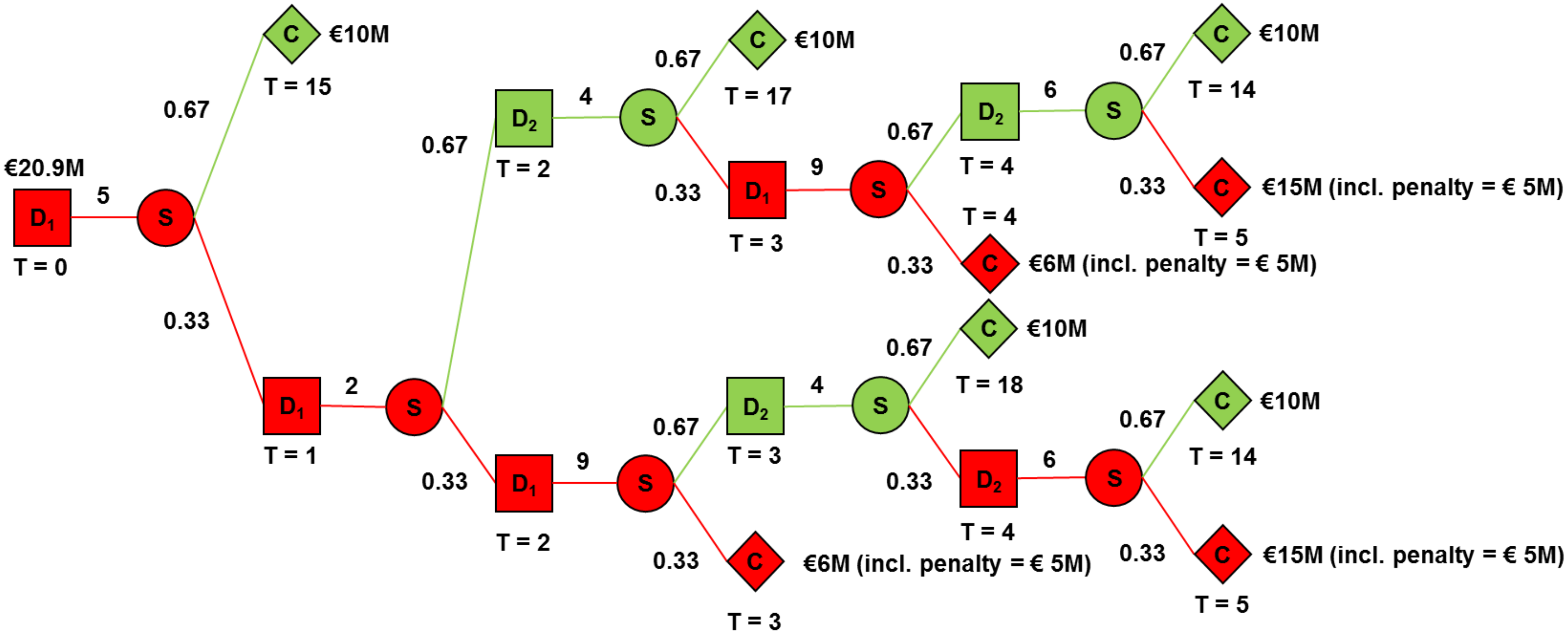
The other scenario assumed is the remediation of CO_2 leakage from the storage complex during the post-injection period. In this case, the operator would initially prioritise the implementation of those techniques that have a relatively higher likelihood of success, spatial extent and response speed, corresponding to decision node D_1, by assigning an equal weight to each of these performance metrics. As a result, only one of the remediation techniques, labelled 2 (see Table 6), would be selected. Once the leakage situation is brought under control, it was assumed that the subsequent decision node D_2

would be based on the preference for techniques, labelled 4 and 6 (see Table 6), that have a relatively higher likelihood of success, spatial extent and longevity. All the rules that were followed previously, for the purpose of enumeration of the decision tree, were also assumed to hold good in this scenario. Figures 5 illustrates an example of a possible remediation portfolio, starting with the injection of polymer-gel for flow diversion in the reservoir. Using backward induction, the expected value of aggregate costs incurred by the operator is €31.4M.



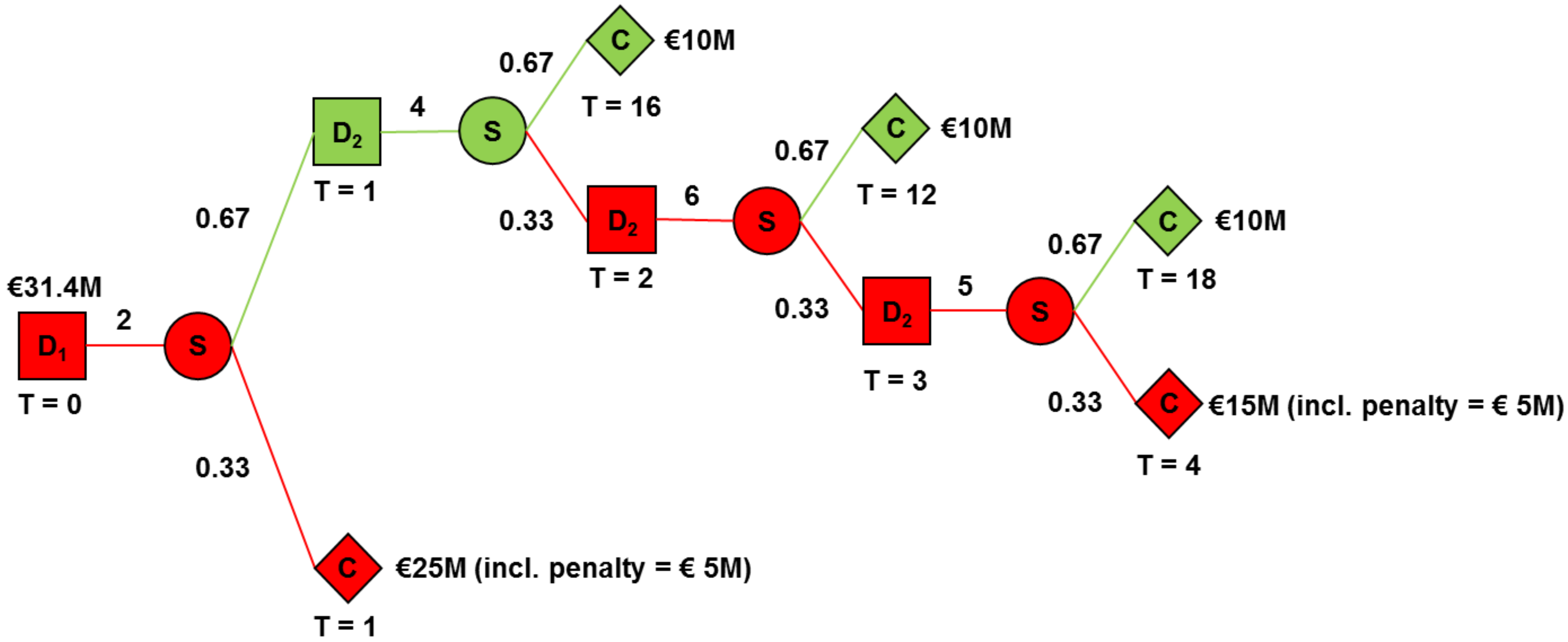
Decision D_1 weights vector: [0.5, 0, 0, 0.5, 0]; Decision D_2 weights vector: [0.33, 0.33, 0.33, 0, 0]

Figure 3. An example of decision tree enumeration for the remediation of leakage detected during the injection period.



Decision D_1 weights vector: [0.5, 0, 0, 0.5, 0]; Decision D_2 weights vector: [0.33, 0.33, 0.33, 0, 0]

Figure 4. Another example of decision tree enumeration for the remediation of leakage detected during the injection period.



Decision D_1 weights vector: [0.33, 0.33, 0, 0.33, 0]; Decision D_2 weights vector: [0.33, 0.33, 0.33, 0, 0]

Figure 5. An example of decision tree enumeration for the remediation of leakage detected during the post-injection period.

4 CONCLUSIONS

In this deliverable report, a methodology was presented for designing a protocol to optimise the selection of a subset of leakage remediation techniques, representing the desirable remediation portfolio, in terms of the expected values of their implementation costs. It benefits from the performance characterisation/ranking of techniques that was previously investigated under the scope of the MiReCOL project based on five performance metrics, namely: (a) likelihood of success; (b) spatial extent; (c) longevity; (d) response speed; and (e) cost efficiency.

The remediation portfolio optimisation approach is based on the principle of structured decision-making under uncertainty. Examples of decision trees were developed based on remediation of leakage detected during the injection and post-injection periods. The enumeration step was used to construct the exhaustive listing of alternatives in the decision tree based on the operator's preference for the performance metrics. In particular, at the time when leakage is detected, emphasis would be aptly placed on those techniques that have a relatively higher likelihood of success and a response speed in both scenarios. As time progresses, the preferences are expected to change depending on the site-specific conditions and leakage severity, which could lead to a complex decision tree, and hence the approach would require software development using efficient data structures and algorithms, in terms of computational speed, in order to cope with the combinatorial requirements of dynamic decision-making.

Furthermore, the backward induction algorithm was implemented to estimate the projections for the aggregate costs of the example remediation portfolios that were developed. For the case where leakage detection occurs during injection, a comparison was made between two possible portfolios. In particular, the portfolio where remediation starts-off with the injection of solid reaction products into the reservoir is more cost efficient than the one which implements polymer-gel injection for flow diversion in the reservoir. However, a full enumeration was not possible, and hence there is scope to further improve on this optimal solution. On the other hand, for the case where leakage detection occurs in the post-injection period, for the assumed set of initial preferences that were chosen, polymer-gel injection for flow diversion in the reservoir appears to be the best technique in order to take speedy control of the situation, based on the performance assessment that was carried out previously.

Thus, the approach for the identification of optimal remediation portfolios presented in this report demonstrates promise for its real world application in the field, if the dynamic scaling of the decision trees is implemented through a dedicated software development activity, which is currently beyond the scope of the MiReCOL project. Nevertheless, the methodology developed is proven and results from this work provide an important input for the handbook of corrective measures that is separately prepared in the project.

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