Risk assessment of CO₂ injection processes and storage in carboniferous formations: a review

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Abstract: Over the last decades, people from almost all over the world have realized that it is necessary to quickly develop strategies for the control and reduction of greenhouse gases (GHG) emissions. Among various GHGs, carbon dioxide (CO₂) is the most abundant GHG. Its underground storage involves less risk and lower levels of dangerousness. The paper briefly describes the most effective technologies available in the market for background processes to storage (capture and transport) CO₂, as well as the more secure solutions for its storage, in particular for the geological storage in carboniferous formations. This paper also outlines the methodologies for the risk assessment involved in storage of CO₂, with a particular focus on cases where the injection is made into unminable coal seams and in abandoned coal mines. Methodologies used for risk analysis are described in detail with particular emphasis on Bayesian network (BN). Some applications regarding the risk assessment of CO₂ injection processes and CO₂ storage in carboniferous formations and contamination of aquifers are presented and analyzed. Finally, based on the applications of BN, several conclusions are drawn.

Key words: risk assessment; underground storage of CO₂; coal mines; monitoring

1 Introduction

There are several ways of mitigating greenhouse gases (GHG) emissions to the atmosphere. The storage of large quantities of carbon in geological formations is presented today as one of the most effective methods with visible results. Carbon dioxide (CO₂) capture and storage (CCS) are a process consisting of the separation of CO₂ from industrial and energy-related sources. Figure 1 brings together, in schematic form, the main sources and some of the possible storage sites.

Storage of CO₂ in deep, onshore and offshore geological formations uses many technologies developed by oil and gas industries, and it has been proved to be economically feasible under specific conditions in oil and gas fields and saline formations [1]. CO₂ can also be stored in carboniferous formations, either in unminable coal seams or in abandoned coal mines. CO₂ can be safely injected and stored at well

Fig.1 Processes of capturing and storing CO₂ [1].

characterized and properly managed sites. Injecting CO₂ in deep geological formations can store it underground for a long period of time. At the depth of 800–1 000 m underground, CO₂ has a liquid-like density that permits the potential for an efficient use of underground reservoirs in porous sedimentary rocks.
Figure 2 illustrates the options for storing CO$_2$ in deep underground geological formations [1]. Other geological options, which may serve as storage sites, include caverns in basalt, organic-rich shale and salt.

As it can be observed in Fig.3, China became the largest emitter of CO$_2$ in 2007. In 2006 it reached a peak of $6.53 \times 10^6$ t per year [2]. Despite being the largest emitter and one of the fastest growing countries, China yet releases much less GHG per capita than any developed country.

China has the major resources of coal in the world. The situation of emission of CO$_2$ is represented in Fig.4. China and other developing countries, such as India, are not submitted to the limits imposed by the Kyoto Protocol. The use of coal as a source of energy is attractive due to its abundance and its low price. However, research and development in technologies for renewable energies, energy efficiency, CCS, etc., should also be considered in emerging countries. The situation in China can be characterized by a large number of abandoned coal mines of about one thousand. Therefore, the storage of CO$_2$ in abandoned coal mines can be a viable option [2].

Geological storage requires to construct facilities to capture large emission sources of CO$_2$, such as the power for electricity production or cement, steel, ethanol, etc.. The captured CO$_2$ is then transported by pipelines or in ships to underground storage sites. Most of the mechanisms related to this technology are not new, since they are already employed in oil industry, or by contractors for management and distribution of natural gas, some industries in the food sector, etc..

Currently, capturing CO$_2$ is costly and energy consuming. The costs obviously depend on the dimensions of the industrial unit and the type of fuel used. There are four basic systems for capturing CO$_2$ from fossil fuels and/or biomass [1].

The environmental impacts from geological storage of CO$_2$ can be integrated into two types, i.e. local environmental effects and global effects on the atmosphere. Global effects may be viewed as uncertainty in the effectiveness of CO$_2$ storage. Local hazards arise from the causes such as the direct effects of elevated gas-phase CO$_2$ concentrations on the shallow surface or near surface, the effects of dissolved CO$_2$ in groundwater, and the effects induced by fluids displacement of the injected CO$_2$.

There are different potential escaping routes for CO$_2$ injected into the carboniferous formations. Risk assessment should be an integral element of the risk management activities, such as the site selection, site characterization, storage system, design, monitoring and remediation if necessary. A possible methodology to assess risks in these situations is Bayesian network (BN). BN is a graphical representation of knowledge for reasoning under uncertainty, and it becomes a popular representation for encoding uncertain expert knowledge in expert system. BN can be used at any stage of a risk analysis, and provides a good tool for decision analysis, including prior analysis, posterior analysis and pre-posterior analysis. Furthermore, they can be extended to influence diagrams, including decision and utility nodes to explicitly model a decision problem.
In 2010, the State Key Laboratory of Geomechanics and Deep Underground Engineering, China University of Mining and Technology (Beijing), was selected to conduct a project on the risk assessment of CO₂ injection and sequestration in coaliferous reservoirs by the State Administration of Foreign Experts Affairs, China. The importance of the project is related to the fact that China is the major producer of coal in the world. Therefore, there are several possibilities for selecting appropriate sites for reservoirs, even in abandoned coal mines. Coal formations contain cleats that impart some permeability to the system. Between cleats, coal has a large number of micropores, into which gas molecules can diffuse and be tightly absorbed. Gaseous CO₂ injected through wells will flow through the cleat system, and diffuse in the coal matrix and be absorbed onto the coal micropore surfaces. If CO₂ is injected into coal seams, it can displace gas methane, enhancing coal bed methane recovery.

This paper reviews the literatures published on geological storage of CO₂ in deep saline aquifers and coaliferous formations, including abandoned coal mines with special emphasis on the problematic risk assessment.

2 Injection and safety storage

2.1 Introduction

CO₂ is a common constituent of the atmosphere, non-toxic. However, high concentrations can be dangerous [3]. An uncontrolled release of CO₂ from an underground reservoir will not have long-term effects once the CO₂ is diluted in air or water, as that happens in cases of highly toxic or nuclear waste. Thus, slow migration of gas toward the surface is not a direct threat to humans. However, high concentrations can be attained by a sudden release or other processes. Due to the high density of CO₂ in relation to air in the case of leakage of large volumes, depressions or enclosures can be created near the earth’s surface, causing loss of consciousness or asphyxiation to humans who are in the vicinity [4].

The main risks of geological storage of CO₂ vary from place to place, mainly depending on such factors [1, 5, 6]:

(1) The configuration of the storage facility, including the geological characteristics of the stratum selected.

(2) The heterogeneity of the sealing caprock.

(3) The heterogeneity of the mass taken as a whole (stratigraphic heterogeneity, existence of discontinuities, etc.).

(4) Knowledge of the existence of abandoned injection/pumping wells nearby.

(5) The adequacy of the injection system.

(6) Changing biogeochemistry.

(7) Geomechanical weathering (generation of cracks and fractures).

(8) Methods of abandonment of the wells when the reservoir reaches the limit.

Duguid et al. [7] suggested that, as one of the first requirements to be met by a site candidate for the reservoir, it was to have several layers of sealing. Thus the system is redundant and it is possible to make early detection of potential problems. If CO₂ escapes, the system gives an indication to the authorities. If the problem is not resolved, the secondary layers of protection is in charge of retaining leakage.

In accordance to Ref. [1], the commercial projects of CO₂ storage in large scale should be adopted if it is assumed that the location is well chosen, designed, operated and monitored. The data available from existing projects suggest that it is very likely that the fraction of stored CO₂ trapped in the first 100 years is over 99%, and it is possible that the fraction of stored CO₂ trapped in the first 1 000 years is over 99%.

2.2 Risks associated with the earlier stages of storage

Various stages leading up to the storage itself cause the changes in the state of stress and strain of the rock mass. In turn, flow paths may be generated, through which CO₂ can escape due to the discontinuities (pre-existing or not), such as faults or other fractures. Associated with the existence of faults, seismic episodes may occur, which may bring more risks to the CCS project.

To understand the influence of entire storage system on the rock mass, it is necessary to study each phase separately. Different phases [8] that may be considered are as follows: (1) drilling and completion of wells; (2) formation dewatering and methane production; and (3) CO₂ injection with or without secondary production of methane.

Wellbore stability is a geomechanical problem that can be encountered during drilling. Rock failure and displacements associated with wellbore instability generate potential leakage paths. These drilling issues and the main causes of instabilities are analyzed in detail in Ref. [9]. The risk of leakage will be minimized by cementing the case. Two constructive methods are
conventionally used in the execution of wells: cased hole wells and open-hole cavity wells. The risks associated with the two methods are analyzed in detail in Refs.[8, 9].

If CO₂ is expected to be stored in unminable coal seams, never considered by the mining industry (due to great depths, the lack of profitability of the project, or poor safety conditions for workers), it is necessary to carry out wells with withdrawal of water, and possibly advantageous to the extraction of methane adsorbed on coal if intended to store CO₂ during drilling.

Injection of CO₂ for enhancing methane production and sequestration will increase pore pressures in the coal seam. If pore pressures exceed pre-development levels, there is a risk that slips would occur. This is conceptually illustrated in Fig.5 [9].

The causes for geomechanical problems and their consequences, and the risks and their factors are summarized in Figs.6 and 7, for wells totally cemented and wells partially cemented with cavities, respectively. More details regarding other situations are referred to Ref.[10].

2.3 Risks associated with the storage

The geological storage of CO₂ means that CO₂ will be retained for hundreds or thousands of years. Therefore, it is necessary to carefully evaluate all potential escape mechanisms. The mechanisms that may occur in unminable coal seams and abandoned mines are presented in Ref.[5]. In terms of risk, the abandoned mines require major rehabilitation work, checking the conditions for sealing wells and shafts, and the removal of all materials that might react with CO₂. The existence of wells abandoned or not in vicinity of reservoir is an important issue to be analyzed in terms of safety. Figure 8 makes a summary of some possible leakages of CO₂.

The assessment of risks associated with the storage of CO₂ in unminable coal seams requires to identify the processes of CO₂ leakage and the probability of occurrence, the escape rate over time, and the implications for a safe long-term storage. A quantitative assessment of uncertainties and risks
associated can only be achieved if the parameters of the reservoir and the physical processes involved are well known.

The risk assessment is done by random selection of input parameters, followed by analysis of results, assigning a risk value, and ultimately the production of statistics for the risk profile. This approach can be implemented by applying the Monte Carlo method or using BN among other methods. It is often based on the assumption that the reservoir properties are random and independent of each other. Other researchers [11, 12] considered the relationships among the parameters, the uncertainty and variability of the data, the uncertainties of model parameters and the uncertainties associated with risk scenarios considered.

In general, the CO$_2$ retained by adsorption on the surface of coal is remained in the deposit, even without caprocks, unless the pressure in the coal mine is reduced through mining. If the pressure drops suddenly, any excess CO$_2$ from coal can flow freely according to one of the mechanisms described previously in the Fig.8. Therefore, it is necessary to ensure that after storing CO$_2$, the coal is never mined [9].

Figure 9 presents a scheme of storing CO$_2$ in carboniferous formations with enhanced coal-bed methane recovery (ECBMR) [5].

Moreover, the complex geometry of a coal mine can also be translated in a simplified manner by a sealed container vertical upwards, according to an idealization of Piessens and Dusar [4]. In a coal mine, CO$_2$ can be stored in the voids, dissolved in water, or adsorbed on the coal matrix. However, coal mines suitable for CO$_2$ sequestration should not be flooded. So either it is a mine without entrance for water (good sealing strata), or, in the most likely case, the CO$_2$ will be disposed of under high pressure. Note that in the first situation, the initial pressure of such reservoirs will be low (near atmospheric pressure), which means that the initial state of pressure is at great unbalance with the hydrostatic gradients. In the second situation, it is necessary to ensure that the sealing caprocks, despite being deformed due to the pressurization of the cavity, are able to resist this pressure without open cracks or cause sliding along existing faults [13]. Figure 11 presents a schematic diagram of three different ways of storing CO$_2$ in a coal mine.

The existence of pumping wells or injection of fluids is a major source of potential escape problems of CO$_2$. The wells are linear infrastructure that makes the
connection between surface and underground reservoirs, crossing all rock strata, even the most impervious. An eventual path to the leakage of CO$_2$ is then created. The sealing caprock of the well, the walls of well, the annular area of interface with the walls, the first layer of cement case and the involved rock mass are the main elements that should be carefully analyzed.

In the presence of water, CO$_2$ becomes carbonic acid, which can affect the integrity of the casing cement, or even the first cement layer that lies between the walls and the rock mass. Thus the resistance of the cement can be affected. In order to prevent this degradation, an extra thick wall and the introduction of additives to the cement should be considered [5]. Figure 12 shows potential escape paths of CO$_2$ along injecting or pumping wells. In abandoned wells, the types of escape mechanisms along the walls are similar to those in the wells still in operation. Path (a) in Fig.12 focuses on the flow through the interface of the well casing and cement layer on the inside face of the coating. Since both materials are very permeable, runoff is very focused in the vertical direction. In path (b), there is an escape mechanism similar to path (a), but it is only between the casing and the cement that leads to the closing hole. In path (c), the mechanism of percolation of CO$_2$ through the cement seal is illustrated. In paths (d) and (e), flow crossing the final layer of concrete and masonry is represented. Path (f) shows another way of leakage between the cement and the strata surrounding the well.

3 Associated risks

3.1 General description

Risk assessment and mitigation strategies are developed with the goal of avoiding major problems described above. There are many definitions for risk assessment. More generally, for an undesirable event $E$ with different consequences, vulnerability levels are associated and the risk [14] can be defined as

$$R = P[E]P[C \mid E]u[C]$$  \hspace{1cm} (1)

where $R$ is the risk; $P[E]$ is the hazard, i.e. the probability of the event; $P[C \mid E]$ is the vulnerability of event $E$; and $u[C]$ is the utility of consequence $C$.

More generally, for different failure events $E_j$, with which different consequences and hence vulnerability levels are associated, expected risk [15] can be defined as

$$E[R] = \sum_j \sum_i P[E_j]P[u(C_i) \mid E_j]u(C_i)$$  \hspace{1cm} (2)

where $P[u(C_i) \mid E_j]$ is the vulnerability to the failure mode $j$, $P[E_j]$ is the probability of failure mode $j$, and $u(C_i)$ is the utility of consequence $i$.

For risk evaluation, it is necessary to identify the tools or models to be used to represent this existing knowledge and to perform risk and decision analyses. Risk assessment and risk management for CCS systems require an evaluation of the hazard and the assessment of the likelihood of the harmful effects. Risk assessment starts with the hazard identification, which refers to the identification of the major possible hazards, and focuses on the likelihood of extent of damage. After the hazard identification, risk characterization is followed, which involves a detailed assessment of each hazard in order to evaluate the risk associated with each hazard [16].

Based on studies presented in several publications [1, 8, 15, 16], nine hazard identification scenarios are characterized (Table 1). Once the risks associated with each hazard are identified, the decision-makers can develop a basis for their evaluation and the time necessarily to develop and carry actions to reduce the risks [16].

3.2 Leakage of CO$_2$ from pipelines or pumping stations and shipping

CO$_2$ from power plants or other industrial facilities...
Table 1. Hazard identification scenarios.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Description</th>
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<tbody>
<tr>
<td>H1</td>
<td>Leakage of CO2 from pipelines or pumping stations</td>
</tr>
<tr>
<td>H2</td>
<td>Leakage of CO2 from shipping</td>
</tr>
<tr>
<td>H3</td>
<td>Slow and steady leakage of CO2 from geological storage</td>
</tr>
<tr>
<td>H4</td>
<td>Fast and large discharge of CO2 from geological storage</td>
</tr>
<tr>
<td>H5</td>
<td>Leakage from geological storage to groundwater</td>
</tr>
<tr>
<td>H6</td>
<td>Leakage of CO2 from geological storage to fossil fuel assets</td>
</tr>
<tr>
<td>H7</td>
<td>Leakage of CO2 that eliminates the benefits of geological storage</td>
</tr>
<tr>
<td>H8</td>
<td>Induced fracturing or seismicity</td>
</tr>
<tr>
<td>H9</td>
<td>Leakage from abandoned coal mines</td>
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</table>

can be transported to storage sites by pipelines. For any transportation option, there are calculable and perceivable risks. CO2 pipelines provide a direct route to harmful human exposure or harmful impacts on animals and plants by producing a local high concentration of CO2 and generating exposures sufficient to harm or kill people, plants and animals [1]. While important risk precautions can be taken to minimize the likelihood of a major pipeline rupture.

The long-distance CO2 pipelines existing in USA are illustrated in Fig.13. Special emphasis on the Cortez pipeline (808 km long), the Sheep Mountain pipeline (660 km long) and the Weyburn pipeline (330 km long) can be made. Measures taken to minimize the risks from CO2 pipelines [1, 16] include: (1) to localize pipelines away from populous areas; (2) to avoid pipelines near populated valleys where leaking CO2 could accumulate to dangerous levels; (3) to monitor pipelines against corrosion and to monitor regularly for leaks; and (4) to install safety valves to shut off the pipeline in case of a large leak.

Leakage of CO2 from shipping can occur in different ways, namely, through collision, foundering, stranding and fire [1]. The accidents can occur due to the poor maintenance of ships, and the crew by inadequately trained people, system failures and human errors. CO2 tankers and terminals are clearly much less at risk from fire, but there is an asphyxiation risk if collision ruptures a tank. The risk can be minimized by making sure that high standards of construction are applied. An accident with a liquid CO2 tanker might release liquefied gas to the surface of the sea. CO2 would behave differently from liquefied natural gas (LNG) because liquid CO2 in a tanker is not as cold as LNG. Its interaction with the sea could be complex. Some of the gas would dissolve in the sea, but some would be released into the atmosphere. With little wind and temperature inversion, CO2 gas might lead to asphyxiation and stop the engines. The risk can be minimized by carefully planning routes and ensuring high standards of training and management [1].

3.3 Slow and fast leakage of CO2 from geological storage

Leakage of CO2 from the geological reservoir can produce two types of hazards, depending on how slow or fast the leakage is [16]. For slow and steady leakage of CO2 from geological storage, the release is too small to cause significant deaths or injuries. However, the leakage can cause local problems including human fatalities. For fast and large discharge of CO2 from geological storage, it can cause large-scale fatalities, although the occurrence is rare. An example is the disaster occurred in 1986 at Lake Nyos in Cameroon. About 1 700 persons and 3 500 cattle were killed when the lake released a large amount of CO2. Possible actions and measures for these hazards can be referred to in detail in Ref.[16].

3.4 Leakage from geological storage to groundwater

CO2 migration from a storage reservoir to the surface potentially affects the shallow groundwater used for potable water and industrial and agricultural needs. Dissolved CO2 forms carbonic acid alters the pH value of the solution and potentially causes indirect effects including mobilization of metals (toxic), sulphate or chloride. It possibly gives the water an odd odor, color or taste. In the worst case, contamination might reach dangerous levels, excluding the use of groundwater for drinking or irrigation [1].

Among other measures to minimizing the leakage for the groundwater [17], it is relevant to develop appropriate inspection methodologies coupled with the use of dynamic BN for risk analysis [15].

3.5 Leakage of CO2 from geological storage to fossil fuel assets

Underground injection of CO2 at high pressures can lead to seepage of fossil deposits through faults and
other discontinuities or not well-sealed wells. The contamination of the fossil reservoir induces a severe economic risk since the contamination decreases the value of the fossil fuel. The probability of this hazard occurrence is similar to that of CO₂ leakage to the groundwater.

Actions to reduce risks of leakage to fossil fuels include: (1) to select reservoir sites that are likely to retain CO₂ for at least a thousand years; and (2) to select sites that are far away from fossil fuel assets.

### 3.6 Leakage of CO₂ eliminating the benefits of geological storage and induced seismicity

Leakage from a reservoir returns CO₂ into the atmosphere. The sequestration of CO₂ is intended to last for a long period of time. Then, when CO₂ leaks at a fast rate, the benefits of the geological storage are eliminated and additional costs are incurred. Some actions can be performed in the case of inadequately sealed wells. Wells can be monitored to ensure that they are adequately sealed and additional activities can be performed to better seal the wells.

Geological carbon sequestration into porous rock masses at a high pressure can induce fracturing and movements along faults. The resultant stresses can fracture the surrounding rock. This may pose two types of risks: (1) brittle failure and associated microseismicity that provide pathways for CO₂ migration; and (2) fault activation that can induce earthquakes large enough to cause damage [1]. So far, only moderate earthquakes have occurred due to injection. Eventual actions to reduce risks induced by fracturing or seismicity are referred to Ref.[16].

### 3.7 Leakage from abandoned coal mines

In coal mines, slow migration towards the surface is not a direct threat to human and nature. However, high concentrations can be reached by a sudden or temporary release of CO₂. Because CO₂ is much denser than air, it could be up to high concentrations in depressions and confined areas near the surface and cause problems to human, which is a known risk that happens in volcanic lakes. Leakage may also occur along infrastructure, case of wells, and faults. The effect of active faults on sealing properties of the overburden is an important safety issue and it should be considered. A technical obstacle for injection of CO₂ into the abandoned coal mines is the low initial reservoir pressure.

More details on the feasibility of CO₂ sequestration in coal mines and eventual actions to be considered to reduce the risk are referred to Ref.[13].

### 4 Preventing risks by monitoring

In order to prevent potential risks, monitoring is needed. Measurements of certain parameters should be made to assess the behavior of the CO₂ system. The monitoring results must be compared with the ones predicted by modeling and risk analysis. The models can be updated after careful interpretation of a set of observed results.

Monitoring is performed for various purposes [1], including: (1) to ensure and document the volume of CO₂ injected into wells, specifically to monitor the conditions of the injection well and to measure the rates of injection, as well as the pressures on the top of the well and in the formation; (2) to verify the amount of injected CO₂ stored by different mechanisms; (3) to optimize the efficiencies of the storage project through the knowledge of the volume storage, the most appropriate injection pressures and the need for drilling new wells; (4) to demonstrate, with appropriate monitoring techniques, that CO₂ is still contained in the intended storage formations; (5) to detect leakages and to provide a early-warning of any occurrence, so that the situation can be remedied by appropriate mitigation measures; (6) to know the integrity of wells that are being used or are abandoned; (7) to calibrate and verify models for determining the performance; and (8) to detect the microsismicity associated with the storage projects.

Before CO₂ storage, it is necessary to measure most relevant parameters to be controlled and to characterize the site, in order to know the initial situation (baseline) that will be used in future comparisons. It is convenient to perform several in-situ tests over different seasons, since some properties have a natural variability. This need is particularly felt when the remote sensors are used, for example, the seismic sensors. This is particularly true for seismic and other remote-sensing technologies, where the identification of saturation of fluids with CO₂ is based on comparative analysis. Monitoring the initial situation is also a prerequisite for geochemical analysis, where anomalies relative to background concentrations [9, 17].

Measurement of CO₂ injection is a common practice in oil and gas fields, and the instruments for this purpose are available in the market. Measurements are made by gauges at the wellhead injection or in the vicinity of the injection tube. The accuracy of measurements depends on a number of factors [1]. For
CO2, the accurate estimation of the density is very important for improving the measurement accuracy. Small changes in temperature, pressure and composition can have large effects on the density.

Measurements of injection pressure at the surface and in the rock formations are also usually performed. Gauges are installed in most injection wells through holes on the surface piping near the wellhead. Measurements of pressure in the well are routine. A wide variety of pressure sensors are available and adequate to monitor pressures at the wellhead or in the rock formations. The data are continuously available. The surface pressure gauges are often linked to shut-off valves that will stop or reduce the injection pressure to a certain limit if the pressure exceeds a pre-determined safe value, or if there is a drop in pressure as a result of a leakage [1]. Fiber-optic pressure sensors and temperature sensors are available. These systems should provide more reliable results, as well as better control of the well. The current state of technology is more sufficient to meet the needs of monitoring rates of injection, and the pressures on the top of the hole. Combining with temperature measurements, the data provide information on the state of the CO2 (supercritical, liquid or gaseous) and precise values of the quantity of CO2 injected. This information may be used for verification and possible updating of the model adopted.

Figure 14 presents a methodology that can be used by monitoring for the long-term integrity analysis of a well in terms of risk evaluation.

The way that CO2 distributes and moves underground can be monitored in several ways. Table 2 [1]

<table>
<thead>
<tr>
<th>Measurement technique</th>
<th>Measurement parameters</th>
<th>Example applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduced and natural tracers</td>
<td>(1) Travel time; (2) Partitioning of CO2 into brine or oil; (3) Identification of sources of CO2</td>
<td>(1) Tracing movement of CO2 in the storage formation; (2) Quantifying solubility trapping; (3) Tracing leakage</td>
</tr>
<tr>
<td>Water composition</td>
<td>(1) CO2, HCO3−, CO3²−; (2) Major ions; (3) Trace elements; (4) Salinity</td>
<td>(1) Quantifying solubility and mineral trapping; (2) Quantifying CO2-water-rock interactions; (3) Detecting leakage into shallow groundwater aquifers</td>
</tr>
<tr>
<td>Subsurface pressure</td>
<td>(1) Formation pressure; (2) Annulus pressure; (3) Groundwater pressure</td>
<td>(1) Control of formation pressure below fracture gradient; (2) Wellbore and injection tube condition; (3) Leakage out of the storage formation</td>
</tr>
<tr>
<td>Well logs</td>
<td>(1) Brine salinity; (2) Sonic velocity; (3) CO2 saturation</td>
<td>(1) Tracing CO2 movement in and above storage formation; (2) Tracking migration of brine into shallow aquifers; (3) Calibrating seismic velocities for 3D seismic surveys</td>
</tr>
<tr>
<td>Time-lapse 3D seismic imaging</td>
<td>(1) P- and S-wave velocities; (2) Reflection horizons; (3) Seismic amplitude attenuation</td>
<td>Tracing CO2 movement in and above storage formation</td>
</tr>
<tr>
<td>Vertical seismic profiling and crosswell seismic imaging</td>
<td>(1) P- and S-wave velocities; (2) Reflection horizons; (3) Seismic amplitude attenuation</td>
<td>(1) Detecting detailed distribution of CO2 in the storage formation; (2) Detecting leakage through faults and fractures</td>
</tr>
<tr>
<td>Passive seismic monitoring</td>
<td>Location, magnitude and source characteristics of seismic events</td>
<td>(1) Development of microfractures in formation or caprock; (2) CO2 migration paths</td>
</tr>
<tr>
<td>Electrical and electromagnetic techniques</td>
<td>(1) Formation conductivity; (2) Electromagnetic induction</td>
<td>(1) Tracking movement of CO2 in and above the storage formation; (2) Detecting migration of brine into shallow aquifers</td>
</tr>
<tr>
<td>Time-lapse gravity measurements</td>
<td>Density changes caused by fluid displacements</td>
<td>(1) Detect CO2 movement in or above storage formation; (2) CO2 mass balance in the subsurface</td>
</tr>
<tr>
<td>Land surface deformation</td>
<td>(1) Tilt; (2) Vertical and horizontal displacements using interferometry and GPS</td>
<td>(1) Detect geomechanical effects on storage formation and caprock; (2) Locate CO2 migration pathways</td>
</tr>
<tr>
<td>Visible and infrared imaging from satellite or planes</td>
<td>Hyperspectral imaging of land surface</td>
<td>Detect vegetation stress</td>
</tr>
<tr>
<td>CO2 land surface flux monitoring using flux chambers or eddy covariance</td>
<td>CO2 fluxes between the land surface and atmosphere</td>
<td>Detect, locate and quantify CO2 releases</td>
</tr>
<tr>
<td>Soil gas sampling</td>
<td>(1) Soil gas composition; (2) Isotopic analysis of CO2</td>
<td>(1) Detect elevated levels of CO2; (2) Identify source of elevated soil gas CO2; (3) Evaluate ecosystems impacts</td>
</tr>
</tbody>
</table>
summarizes various techniques and their applications to CO₂ storage projects. The applicability is different from place to place and from reservoir to reservoir. A case study of monitoring is conducted at Sleipner gas field in the middle of the North Sea. One Mt CO₂ has been injected at this reservoir per year since September 1996 [1, 17]. CO₂ is injected into salt water containing sand layer, called Utsira formation, 1 000 m below sea bottom. In 1999, the project started to monitor CO₂ behavior and has established a baseline for the first seismic survey. The project is being carried out in three phases (Phase 0, 1 and 2). The last phase involves data interpretation including monitoring and model verification. The transport of CO₂ plume in the storage formation has been monitored successfully by seismic time-lapse surveys (Figs.15 and 16). Work at Sleipner demonstrates that conventional time-lapse P-wave seismic data can be a successful monitoring tool for CO₂ injected into a saline aquifer with CO₂ accumulation [18].

5 Development of methodologies for risk evaluation

5.1 General

There are a number of models available for data analysis and representation, including event trees, rule-based systems, fuzzy-rule based systems, artificial neural networks, and BN. There are also several techniques for data analysis such as classification, density estimation, regression and clustering [15].

Knowledge representation systems (or knowledge based systems) and decision analysis techniques were both developed to facilitate and improve the decision-making process. Knowledge representation systems use various computational techniques of artificial intelligence for representation of human knowledge and inference. Decision analysis uses decision theory and principles supplemented by judgment psychology [19]. Both are emerged from research done in the 1940s, regarding development of techniques for problem solving and decision making. More recently, there has been a resurgence of interest by many artificial intelligence researchers in the application of probability theory, decision theory and analysis to several problems, resulting in the development of BN and influence diagrams, an extension of BN designed to include decision variables and utilities.

5.2 BN

Over the last decade, BN has become a popular representation for encoding uncertain expert knowledge in expert systems [20]. BN can be used at any stage of a risk analysis, and may substitute both fault trees and event trees in logical tree analysis. While common causes or more general dependency phenomena pose significant complications on the classical fault tree analysis, this is not the case with BN. They are in fact designed to facilitate the modeling of such dependencies. BN provides a strong tool for decision analysis, including prior analysis, posterior analysis and pre-posterior analysis. Furthermore, they can be extended to influence diagrams, including decision and utility nodes in order to explicitly model a decision-making problem [21].

A BN is a graphical representation of knowledge for reasoning under uncertainty. It is a concise representation of the joint probability of the domain that is being represented by the random variables. It is
a graph [22] that consists of: (1) a set of random
variables that make up the nodes of the network; (2) a
set of directed links between nodes (these links reflect
cause-effect relations within the domain); (3) each
variable has a finite set of mutually exclusive states; (4)
the variables together with the direct links form a
direct acyclic graph (DAG); and (5) attached to each
random variable \( A \) with parents \( B_1, B_2, \ldots, B_n \), there is
a conditional probability table \( P(A | B_1, B_2, \ldots, B_n) \),
except for the variables in the root nodes. The root
nodes have prior probabilities.

Figure 17 is an illustration of a simple BN. The
arrows going from one variable to another reflect the
relations between variables. In this example, the arrow
from \( C \) to \( B_1 \) means that \( C \) has a direct influence on \( B_1 \).

\[ \text{Fig.17 An illustration of a simple BN.} \]

Specifically, a BN is a graphical and concise
representation of a joint probability distribution over
all the variables, taking into account that some
variables are conditionally independent. The simplest
conditional independence relationship encoded in BN
is that a node is independent of its ancestors, given its
parents, i.e. a node only depends on its direct parents.
Thus, the joint probability of a BN over the variables
\( U = \{A_1, A_2, \ldots, A_n\} \) can be represent by the chain rule:
\[
P(U) = \prod_i P(A_i | \text{parents}(A_i))
\] (3)
where \( \text{parents}(A_i) \) is the parent set of \( A_i \).

Since a BN defines a model for variables in a certain
domain, its relationships can be used to answer
probabilistic queries about them. The most common
types of queries are as follows:

(1) A priori probability distribution of a variable:
\[
P(A) = \sum_{X_1} \cdots \sum_{X_k} P(X_1, \ldots, X_k, A)
\] (4)
where \( A \) is the query-variable; and \( X_i \) (\( i = 1, 2, \ldots, k \))
is the remaining variables of the network.

(2) Posterior distribution of variables given evidence
(observation). This query consists of updating the state
of a variable (or subset of variables) given the
observation:
\[
P(A | e) = \frac{P(A, e)}{\sum_{x_1} \cdots \sum_{X_k} P(X_1, \ldots, X_k, A, e)}
\] (5)
where \( e \) is the vector of all the evidence.

5.2.1 Inference for BN

There are two main groups of inference algorithms:
extact inference method and approximate inference
algorithm. The most common and exact inference
method is the variable elimination algorithm that
consists of eliminating (by integration or summation)
the non-query, non-observed variables one by one by
summing over the product. The approximate inference
algorithms are used when exact inference may be
computationally infeasible, such as that in temporal
models (dynamic BN), where the structure of the
network is very repetitive, or in highly connected
networks.

(1) Dynamic Bayesian network (DBN)
DBN is the BN that represents sequences of
variables. It is often applied to temporal data such as
speech recognition, visual tracking, and financial
forecasting; however, it is also used in sequence data
analysis, e.g. Biosequence analysis, text processing
among others. It is mostly used for the problems such
as classification, state estimation, fault diagnosis,
prediction, etc..

A specific case of a DBN is presented in Fig.18.
This DBN represents a hidden Markov model (HMM),
where each state \( X_i \) generates an observation \( Y_i \). The
structure and the variables are repeated over time.

\[ \text{Fig.18 DBN representing a HMM.} \]

In order to represent such DBN, we need: (a) initial
distribution \( P(X_1) \); (b) transition model, i.e. transition
probability distributions \( P(X_{i+1} | X_i) \); and (c) sensor
model \( P(Y_i | X_i) \).

(2) Inference in DBN

The problem of inference in DBN is NP-hard. There
are several algorithms divided into two groups, i.e.
extact inference algorithm and approximate algorithm.

For exact algorithm, we need: (a) forwards-
backwards smoothing algorithm (on any discrete-state
DBN); (b) the frontier algorithm; (c) the interface
algorithm; and (d) Kalman filtering and smoothing.
For approximate algorithm, we need: (a) the Boyen-Koller (BK) algorithm; (b) factored frontier (FF) algorithm; (c) loopy propagation algorithm (LBP); (d) Kalman filtering and smoother; (e) stochastic sampling algorithm; (f) importance sampling or MCMC; (g) particle filtering (PF); and (h) influence diagrams (decision graph).

BN can serve as a model of a part of the world, and the relations in the model reflect causal impact among events. However, the reason we are building models is to use them when making decisions (i.e. the probabilities provided by the network are used to support some kinds of decision-makings). Decision graph and influence diagram are both an “extension” of BN. In addition to nodes for representing random variables, influence diagrams also provide node types for modeling alternatives and utilities. Besides the chance nodes that denote random variables and correspond to the only node type available in belief networks, the decision nodes are also modeled. A decision node indicates a decision facing the decision-maker (similar to decision nodes in decision trees) and contains all alternatives available to the decision-maker at that point. The third node type provided by these diagrams is the utility node. These nodes represent the utility function of the decision-maker. In the utility nodes, utilities are associated with each of the possible outcomes of the decision problem modeled by the influence diagram.

Direct links between nodes represent influences. Links between two chance nodes have the same semantics as in the belief networks. Other links in an influence diagram may also represent a temporal relation between the nodes involved. For example, a link from a decision node to a utility node indicates that not only the choice of action influences the utility, but also the decision precedes the outcome in time.

Influence diagrams are useful in structuring a decision problem. While, for example, decision trees are more effective in presenting the details of a decision problem, influence diagrams more clearly show the factors that influence a decision. Figure 19 illustrates a simplified scheme of an influence diagram. It is composed of two chance nodes (“threat” and “warning device”), one decision node (“decision”) and a utility node (“consequence”). In this specific example, the chance node “threat” can represent the occurrence or not of a natural threat (for example, a tsunami or a hurricane). The chance node “warning device” represents the fact that a warning alarm may be issued or not. The decision node represents the decision evacuating a population or not. The utility node (“consequences”) represents the consequences (expressed in utilities of the decision) in combination with the occurrence or not of the threat. The warning device issuing an alarm depends directly on the possibility of occurrence of the threat. The decision of evacuating the population or not will depend directly on the warning device issuing an alarm. Finally, the consequences will depend on the decision taken and whether or not the threat actually happens.

There are mainly four types of connections for structural influence in a decision graph. They are represented in Fig.20.
The first one (Fig.20(a)) is used when a decision (decision 1) affects the probabilities of event 1, i.e. decision 1 is relevant for event 1. In Fig.20(b), the outcome of event 1 affects the probabilities of event 2, i.e. event 1 is relevant for event 2. This is a typical BN without decision included. The type of connection in Fig.20(c) is used when decision 1 occurs before decision 2, i.e. decisions 1 and 2 are sequential. Finally, Fig.20(d) represents a connection used when decision 1 occurs after event 1. In this case, the outcome of event 1 is known when making decision 1.

Besides the structural influences described in Fig.20, there are also value (utilities) influences such as the ones illustrated in Fig.21.

In Fig.21(a), the value (utility) depends on the (uncertain) event, for example, a manufacturing cost depends on the (uncertain) availability of a certain input. In the second value influence (Fig.21(b)), a decision influences the value (utility). For example, a manager’s decision influences the profit of a plant.

5.2.2 Inference for influence diagrams

The inference process in an influence diagram consists of computing the expected utility associated with different decisions or strategies. As in BN, there are two groups of algorithms that can be used to make inference in an influence diagram exactly and approximately. The most basic way to solve an influence diagram is to unfold it into a decision tree and solve it. However, if one wants to take advantage of the structure of an influence diagram and encoded conditional independences, one of the most common issues is the variable elimination algorithm for influence diagrams, which has many similarities to the variable elimination technique described for BN. For more details, it can be referred to Refs.[23, 24].

6 Application of BN

In this section, the examples of BN and DBN are presented to illustrate their potential use for risk analysis in CO₂ injection processes. The first example is developed for a situation where one wants to determine whether or not it is beneficial to inject CO₂ in carboniferous formations at a certain location. This example, is based on hazards H₃ and H₄ defined previously. In this example, the decision-maker is looking at different mitigation measures (for reducing the leakage of CO₂), assessing the risk of each option and choosing the one that can minimize it. Finally, an example of a DBN is presented to illustrate the use of DBN coupling with results of a monitoring system.

6.1 Risk analysis for storage of CO₂

For the risk analysis due to CO₂ injection in carboniferous formations, a BN is developed, as presented in Fig.22. The involved variables are associated with:

- Sedimentary strata conditions over the carboniferous formations. Three values are adopted for the formations: good, bad and very bad.
- Coal seams characteristics. Three distinct values are taken: good, bad and very bad.
- Combined characteristics due to the association of sedimentary strata and coal seams. The values are attributed in function of the properties defined to both formations.
- Geomechanical characteristics of the wells. Two values are adopted for the shaft: good and bad in function of the existing corrosion.
- Corrosion of the well. Two levels are considered: level 1 (reasonable) and level 2 (bad).
(6) Existence of faults. Two hypotheses are considered: yes and no.

(7) Escape of CO\textsubscript{2}. For this situation, the value is considered for the combined characteristics of both formations involved (coal seams and sedimentary strata), the existence of wells and faults, and course whether CO\textsubscript{2} is injected or not.

(8) Injection of CO\textsubscript{2}. For this situation, two distinct values (yes or no) are considered.

(9) Utilities (consequences). For the utilities, the calculated result permits to be concluded whether the rehabilitation measures are adopted or not.

(10) The calculated risk depends on the escape of CO\textsubscript{2} or not, and the existence of faults. The following three values are adopted: high, average and low.

In Tables 3 to 9, the local and conditional probabilities associated with each variable of the BN are represented. The quantification can be based on expert judgment or available data, or a combination of both. In this case, all the values are given for illustrative purposes.

**Table 3** Sedimentary strata and coal seam characteristics.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Sedimentary strata</td>
<td>0.333</td>
</tr>
<tr>
<td>characteristics</td>
<td></td>
</tr>
<tr>
<td>Coal seam characteristics</td>
<td>0.333</td>
</tr>
</tbody>
</table>

**Table 4** Combined characteristics of sedimentary strata and coal seams.

<table>
<thead>
<tr>
<th>Sedimentary strata characteristics</th>
<th>Coal seams characteristics</th>
<th>Combined characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Good</td>
<td>Good (Yes)</td>
</tr>
<tr>
<td></td>
<td>Bad</td>
<td>Good (No)</td>
</tr>
<tr>
<td></td>
<td>Very bad</td>
<td>Bad (Yes)</td>
</tr>
<tr>
<td>Bad</td>
<td>Good</td>
<td>Bad (No)</td>
</tr>
<tr>
<td></td>
<td>Bad</td>
<td>Very bad</td>
</tr>
<tr>
<td>Very bad</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bad</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very bad</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5** Characteristics of the wells.

<table>
<thead>
<tr>
<th>Corrosion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>0.3</td>
</tr>
<tr>
<td>Level 2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Table 6** Corrosion of wells.

<table>
<thead>
<tr>
<th>Corrosion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>0.5</td>
</tr>
<tr>
<td>Level 2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 7** Escape of CO\textsubscript{2}.

<table>
<thead>
<tr>
<th>Leakage CO\textsubscript{2}</th>
<th>Faults</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Table 8** Damage values.

<table>
<thead>
<tr>
<th>Injection of CO\textsubscript{2}</th>
<th>Damage</th>
<th>Utilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>High</td>
<td>–40</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>–20</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>20</td>
</tr>
<tr>
<td>No</td>
<td>High</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 9** Utilities associated with different scenarios and decisions with CO\textsubscript{2} injection.

<table>
<thead>
<tr>
<th>Combined characteristics</th>
<th>Well characteristics</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good (Yes)</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Good (No)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Bad (Yes)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Bad (No)</td>
<td>0.2</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.99</td>
</tr>
<tr>
<td>Bad</td>
<td>Good (Yes)</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Good (No)</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Bad (Yes)</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Bad (No)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Very bad</td>
<td>Good (Yes)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Good (No)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Bad (Yes)</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Bad (No)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Applications were performed through the software Genie (http://genie.sis.pitt.edu/downloads.html). Two hypotheses (A and B) were considered, as assigned in Table 10.

**Table 10** Different hypotheses considered in the BN.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Sedimentary strata</th>
<th>Coal seams</th>
<th>Wells</th>
<th>Corrosion</th>
<th>Existence of faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B</td>
<td>Good</td>
<td>Bad</td>
<td>—</td>
<td>Level 2</td>
<td>—</td>
</tr>
</tbody>
</table>

These are two different hypotheses that we consider and want to assess. The risk associated with each hypothesis (A or B) are calculated to make a decision on whether or not CO\textsubscript{2} at that location is injected.

For hypothesis A, Fig.23 shows the induced diagram with probabilities calculations. The results demonstrate clearly that it is beneficial to inject CO\textsubscript{2} in the coal seams. For the hypothesis B, Fig.24 shows that the BN diagram recommends not to inject CO\textsubscript{2} in the coal seams.
Fig. 23 Diagram for hypothesis A.

Fig. 24 Diagram for hypothesis B.

Another BN is presented in Fig. 25 when the active faults are considered. The consequences in this situation can imply the existence of induced earthquakes.

Fig. 25 BN for risk analysis of storage of CO₂ with the existence of active faults.

6.2 Contamination of aquifers by CO₂

Contamination of aquifers corresponds to the hazard $H_5$—leakage from geological storage to groundwater, according to different hazards defined in Table 1. CO₂ injected into the ground will be dissolved into water, including pore water between grains or minerals in the geological formations. Dissolution into water can be problematic. The water will be acidified, which allows it to degrade geological formations, and the water saturated with CO₂ is not suitable for drinking.

In order to deal with this situation, the BN is developed. DBN is adopted to evaluate the situation of contamination of aquifers due to the leakage of CO₂.

Two different models are built. One, a prediction model, is employed to model and predict the CO₂ leakage and the influence in the contamination on the aquifer, based on water quality measurements, as described in Fig. 26, for different instants of time (slice 0 until slice $n$). The other, a decision model, is based on decision graphs indicated in Fig. 27. The decision is made on the optimal remedial measures solution for the problem that can pass through the decision without injecting CO₂ any more.

Fig. 26 Modeling the contamination of the aquifer by leakage of CO₂.

Fig. 27 Decision model based on the water quality measurements.

The way that the model works is listed as follows (Fig. 28):
(a) Step 1: observation (water quality measurement) is made at time \( t_0 \) and enters into the network (in grey).

(2) Step 2: the evidence is propagated through the network at time \( t_0 \), and the probability of leakage is determined.

(3) Step 3: the evidence is propagated through into the future, and the probability of leakage in the next slice of time is determined.

Once the prediction model has been employed, one can use its results (Fig.29) to determine the optimal remedial measure, which can be invalid if no remedial measure is considered, by minimizing the risk. Figure 30 shows the decision model with evidence (coming from the prediction model) entered into the network.
The results of the execution of this model are presented in Fig.31. The results show that the best decision given the water measurement at time $t_0$ is not to apply a remedial measure. These steps are then repeated for each slice of time.

7 Conclusions

This paper describes briefly the most effective technologies for CCS projects. Geological carbon sequestration presents the possibility to reduce emissions of CO$_2$ into the atmosphere at a low cost compared to many other options. China has exceptional conditions to store CO$_2$ in carboniferous formations, particularly in abandoned coal mines.

Geological carbon sequestration entails risk that may be large and significant. However, risks can be limited or reduced. Development of methodologies for risk evaluation based on BN has been made and some relevant applications have been performed with particular emphasis on the development of DBN for the hazards related to the leakage from geological storage to groundwater.

Based on the applications of BN, several conclusions can be drawn:

1. In the risk management, BN is a powerful tool in the decision analysis, including priori and posteriori analyses.
2. BN presents the extension of influence diagrams, including the uses of decision nodes and utilities nodes.
3. BN allows combining the knowledge of experts and available data through statistical methods.
4. The beneficial use of DBN in decision processes with time is very relevant to the application made.

The developed models just show how a technique like BN can be used to assess risk in CO$_2$ sequestration problems. All the numbers are given for illustrative purposes. The structure of the BN, however, comes from expert knowledge (based on different hazard scenarios). The framework itself works (prediction and decision models). It has been already applied to a tunnel project case (Porto Metro, Portugal), but it can be applied to any problem where one has observations in time and space and wants to assess risk and minimize it by making the “optimal” decision, that in CO$_2$ case means to apply a mitigation measure or not.

Acknowledgments

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