Developing a method to screen and rank geological CO_2 storage sites on the risk of leakage

Final report

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List of abbreviations and symbols

A,B	Fuzzy sets
°C	Degrees Celsius
CCS	Carbon Capture and Storage
CM(x)	Completeness check
CO_2	Carbon dioxide
COG	Centre of gravity (defuzzification method)
DRA	Deterministic risk assessment
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
FEP	Features, events, processes
GIS	Geological information system
H_2S	Hydrogen sulfide
HSE	Health, safety and environment
I	Implication or conjunction operator
K	Number of rules in a rule base
MAUT	Multi attribute utility theory
N_r	Number of rules
NUSAP	Numeric, Unit, Spread, Assessment, Pedigree
N_x	Number of fuzzy sets
Pa	Pascal
PDF	Probability density function
PRA	Probabilistic risk assessment
R	Fuzzy relation
RA	Risk assessment
s	Property score
S	Attribute score
u	Utility score
UGS	Underground Gas Storage
w	Weight factor

α_i	Degree of fulfillment
$\mu(.)$	Membership degree, membership function
Π	Direct product
$\in$	Set membership (element of…)
$\forall$	Universal quantification (for all…)
$\exists$	Existential quantification (there exists…)
$\wedge$	Intersection, logical AND, minimum
$\circ$	Sup-min (max-min) operator
ε	Degree of coverage
$\Re$	Real numbers
$\subset$	Subset

Abstract

Geological storage of carbon dioxide (CO_2) has been proposed as one of the options to prevent CO_2 emissions into the atmosphere. Assessments of long-term performance related to geologic CO_2 storage needs a robust and reliable framework. One of the first steps in such a framework is site-selection, which requires site-specific research. Important criteria here are risks associated with the CO_2 storage. A safe storage location, capable of sequestering CO_2 for the long term at a minimum of risk, is essential to contribute to global CO_2 reductions and to gain public acceptance. This thesis presents the development of a methodological framework to screen and rank potential geological storage sites based on their posed leakage risk when only limited data is available. This is done by exploring the concept of geological storage, leakage risks involved and risk assessment methodologies.

The main health, safety and environmental risk treated by geological CO_2 storage is the risk of leakage, both in magnitude and impact. Leakage from the targeted reservoir could occur in many ways; via (abandoned) wells and faults will be the most likely pathways, possibly releasing large quantities of CO_2 over time. The cap rock may also be affected by the CO_2 and subject to failure. Physical impacts from CO_2 seepage at the surface may be notable on a local scale (even in a short time frame) where it may negatively affects flora and fauna.

When detailed, site-specific data, knowledge and models are available, risk assessments can be performed in two different ways: either deterministic or probabilistic. In case only generic information is available different assessment methods must be considered. Qualitative risk assessments are often applied here because of their ability to incorporate and formalize subjective knowledge when there is a lack of data, time and expertise. Examples are the use of scenario analysis with FEPs (features, events, processes) and a screening tool based on a multi attribute utility theory (MAUT). This last method was a starting point for developing a framework in which different attributes of geological reservoir (trapped structures) could be assessed to semi-quantitatively describe its performance with respect to leakage risk. The system decomposition is based on the assumption that leakage risk can be divided into categories of concern. Of primary concern are those attributes that in general influence leakage risk to the greatest extent. These are the wells and faults. Of a lower order is the secondary concern, represented by the primary seal. Tertiary concerns are the reservoir itself, the secondary seal(s) and the overburden which to a lesser extent affect the risk of leakage.

Describing leakage risk is more complicated than assessing separate aspects of a storage site. The MAUT framework could not deal adequate with the system complexity. The causal interaction and relationships between system properties could not be implemented, for which a second attempt based on fuzzy logic was undertaken. Fuzzy logic allows the incorporation of imprecise, qualitative knowledge in a systematic way. We feel that modelling with linguistic expert knowledge is suitable for geological representations because of its imprecise

character. Within fuzzy modelling, logic connectives like if-then are involved to define (semi) qualitative relationships among system properties in the form of rules. The use of fuzzy sets allows the generalization of the information used to describe the behaviour of the system and so has the ability to cope with complex non linear systems. Despite its fuzzy character it is fairly transparent and interpretable. The framework we developed, using fuzzy logic principles, has been applied to a set of fifteen different storage sites (only nearly-depleted gas fields and aquifers) in the Dutch onshore region. The Permian, mid-Jura and Tertiary aquifer traps assessed proved to pose the lowest leakage risk. All gas fields scored fairly even, only the Bergermeer gas field (Permian age) scored better because of its excellent primary seal conditions. This indicates that Permian sites are very suitable for CO_2 sequestration, but more attention should be given to leakage through faults and abandoned wells. Triassic sites on the other hand are less suitable and may even be avoided because of bad primary seal conditions. If CO_2 sequestration is considered in Triassic sites, leakage through cap rock should receive much observation.

It can be concluded that ambiguous concepts with inherent uncertainties and complex behaviour, such as geological CO_2 storage, can often not be dealt with in an easy and transparent way. Especially not when there is a data shortage, the available data has uncertainties and the process described with the data is not understood to its full extent. The involvement of expert knowledge is inevitable in stages where these hiatus exist. Consultancies and questionnaires did showed largely comparative results, indicating a high degree of consensus among experts. The proposed fuzzy logic framework formalizes expert knowledge and contributes to how these complex problems may be dealt with (semi) qualitatively. The results were in agreement with a priori knowledge, but this framework is one of the first attempts to structure and apply that knowledge for purposes of screening and ranking. In spite of some implementation and methodological disadvantages, the results presented suggest that fuzzy set theory, approximated reasoning and rule-based fuzzy modeling helps to construct a workable model. This model can cope with physical insight of the system, subjective uncertainty (e.g. expert knowledge) and imprecise data in a transparent and consistent manner. However, detailed quantitative site research should always be part of a selection procedure and this methodological framework could only be part of a pre-selection procedure. Modifications, refinements and extensions to improve the framework are possible through further use and application and e.g. external validation.

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1 Introduction

1.1 General introduction

Worldwide greenhouse gas emissions still increase, with, what is likely to be irreversible effects on the environment. To minimize the negative effects that greenhouse gasses are associated with, reduction targets have been determined according to the 1997 Kyoto Protocol. A leading role in these targets is the reduction of emitted carbon dioxide (CO_2), which is currently causing the biggest impact in the face of global climate change. Replacement of fossil fuels by other energy sources and measures to reduce the primary energy demand are important paths of achieving this goal. Another much more controversial path is the capturing and storage of CO_2 (CCS) from the combustion or conversion of fossil fuels into long-term sinks, recently beginning to receive much more recognition in the wake of the Kyoto Protocol (Lyngfelt, 2001).

Ultimately, the long-term sinks for storing atmospheric CO_2 will be in the oceans (through long-term equilibration with the atmosphere), in terrestrial biomass (CO_2 fertilization), and in crustal rocks as carbonates or kerogen. In the meantime, the most likely traps for initial sequestration efforts based on current technology and experience are geological reservoirs, including abandoned and producing oil and gas fields, unminable coal seams, and deep brine-filled sedimentary formations (Benson, 2002).

Geological storage of CO_2 is a much debated and studied concept over the last decade and has transformed from limited interesting to a potential major greenhouse gas mitigation option. The origin for this shift has a number of reasons. The successfully completed pilot, demonstration and commercial storage projects increased the confidence level in this technology and encouraged further research. Also the confidence of the industrial sector, believe in a broad portfolio of mitigation options to reduce atmospheric CO_2 concentrations and the significant contributions geological storage could make are important. However, storing large amounts of CO_2 creates the potential hazard of accidental release, and exposure to high concentrations of CO_2 poses significant human or ecological risks (Holloway, 1996). Understanding those risks is essential to establish standards and a regulatory framework required for large-scale application of underground CO_2 sequestration (Damen et al., 2003). This makes risk assessment, management and remediation essential to gain both public acceptance and functional efficiency of CO_2 storage as a greenhouse gas mitigation option.

One of the crucial steps prior to actual injection of CO_2 into the subsurface is the selection process of a site. Many technical and non-technical issues must be addressed in such a CO_2 storage site selection procedure. Geological, geotechnical, regulatory, facility, economic and community factors must be considered, where long-term safety plays a major role. To minimize health, safety and environmental (HSE) impacts from CO_2 leakage it is elementary to select a site with sufficient qualities. From this perspective, candidate sites should at least be capable of storing the CO_2 over long timescales (>1000 years) with a minimum of leakage risk and the possibility to proper monitoring. A selection procedure for CO_2 storage sites can aid in the development of scenarios towards a CO_2 distribution and sequestration network that is ongoing.

1.2 Reason to study

1.2.1 Ongoing research

The field of CO_2 storage and risk assessments is a heavily studied area. From the many ongoing R&D activities, risks and uncertainties in CO_2 storage are priorities at the moment. Especially leakage deserves much attention, since this is the most obvious risk that storage sites pose for humans and the environment.

Ongoing R&D programs where the discipline of risk assessments explicitly receives much attention are for instance CO_2 Geonet, Castor and the IEA Greenhouse Gas R&D Programme (IEA GHG). Within the CO2 Geonet network of excellence the Risk and Uncertainty research area, e.g. data and risk uncertainties, HSE risks and long term security are topics in order to gain regulatory and public acceptance of CO_2 storage. Within CASTOR (CO_2 from capture to storage), the subproject 'CO_2 storage performance and risk assessment studies' has the objective to develop and apply a method for site selection and the secure management of storage sites by improving assessment methods, defining acceptance criteria, and developing a strategy for safety-focused, cost-effective site monitoring. The Risk Assessment Network within the IEA GHG program has a more covering nature. Its objective is to develop an open and transparent process to allow different RA approaches and their results to be understood.

1.2.2 Need to screen and rank

For the evaluation of site specific HSE risks associated with geological storage of CO_2, several methodologies have been developed in the last decade. Almost all of them are based on quantitative mathematical modeling (e.g. Wildenborg et al, 2002, Walton et al, 2004, Bowden et al, 2001) and only a few semi-qualitative assessments (e.g. Oldenburg, 2005, Bachu, 2002). These quantitative methods comprise major involvement of many experts, detailed studies and extensive modeling work. To conduct an assessment of a large set of potential storage sites for e.g. a pilot study site pre-selection, these methods can not be employed because of time and money limitations. A new, simplified screening method for early phase site selection would be helpful. However, minor effort have been made to develop a framework in which storage sites can be assessed when there is a lack of detailed knowledge and a limited set of data. Such a screening and ranking assessment could reveal preferential sites and identify sites with a disproportional share of possible HSE risks. Consequently, also a more accurate and realistic valuation of the total technical CO_2 storage potential can be deducted with this assessment. High risk sites and/or sites which would need substantial amounts of effort to reduce the risk and so increase safety, may be disregarded from further research and storage capacity estimations.

1.3 Research objective

The objective of this study is to develop a methodological framework to screen and rank CO_2 reservoirs based on their HSE risk that should enable us to:

- Integrate theoretical knowledge, expert knowledge and data in a consistent, systematic and transparent fashion
- Cope with uncertainty in the knowledge domain.

To test and apply the method, a set of different reservoirs (aquifers and (non)-depleted gas fields) will become subject of assessment. Outside the direct scope of this thesis, but valuable input in many ways, the Dutch onshore CO_2 storage potential in structural aquifer traps is identified and characterized in a separate study (TNO, in progress).

1.3.1 Main research question

Given the public available information on the subsurface for basic site characterization, is it possible to screen and rank potential CO_2 storage reservoirs with the purpose of early site selection based on their HSE risk posed, and if so in what methodological framework?

1.3.2 Sub research questions

The main research question submitted above can be answered adequately only when all the sub-questions are resolved. The following series of sub-questions are introduced:

- What risk assessment methods are applied at current CO_2 storage projects? How are risks assessed in those methods and which features can be used for our purpose?
- What assessment criteria are suitable for ranking CO_2 storage reservoirs, based on HSE risks? Which information is available in the public domain and how can we use it for our purpose?
- How can we deal with uncertainty in the knowledge domain?

1.4 Methodology

The methodology used here is based on theory and practice. It includes a literature review, expert consultancy and iterative method testing. The study is performed at TNO-B&O because of their leading work in risk management and the availability of knowledge and data.

The process includes three stages:

- a literature review on the concept of CO_2 storage and risk assessment,
- the development of a conceptual framework and methodological approach, and
- expert consultancy.

Literature review

An extensive literature review is performed throughout the whole thesis on the topics of CO_2 sequestration and risk management. Especially with regard to the geological conditions of CO_2 sequestration sites, long term (HSE) safety assessment frameworks, and knowledge integration methodologies.

Developing a conceptual framework and methodological approach

With the information and knowledge from the literature study, iteratively methods are to be developed, applied and tested, based on existing risk assessment procedures. Expert consultancy is essential in the realization process of such methods.

Expert consultancy

Throughout the whole thesis many experts from different institutes are to be consulted, considering the complexity of the problem and its multi disciplinary character. By meeting professionals with experience in the CO_2 storage and risk assessment disciplines a huge contribution to the study will be given.

1.5 Reading guide

The information is presented in six chapters. The second chapter will give an overview of the concept of geological CO_2 storage. After general aspects the different storage concepts relevant for this study are briefly explored. Then an elaboration on risk in general and specifically for leakage risks associated with CO_2 storage is given in chapter three. In chapter four different methodologies towards risk assessments are discussed and how they are applied to assess HSE risks of CO_2 storage. One of the methodologies which we proposed and applied in this study is elaborated in chapter five. Chapter six presents the results from the developed methodology and a sensitivity analysis. This thesis finalizes with a discussion, conclusions and recommendations.

2 Geological CO_2 storage

2.1 General aspects

2.1.1 CO_2 characteristics

Carbon dioxide under atmospheric circumstances is a thermodynamically stable gas, with a density of 1.872 kg/m^3. To store large quantities of CO_2 subsurface in a practical (least volume) way, it is necessary to have CO_2 available at a high density. For this purpose CO_2 must be in a supercritical state, i.e. the temperature or pressure should be above the critical point of CO_2. When temperatures exceed 31.26 °C and pressures exceed 7.398 MPa (critical point) CO_2 is in a supercritical state, see Figure 1. At these conditions the density of the CO_2 is comparable to the liquid phase, while the diffusion coefficient is comparable to that in the gas phase. The increase of density depends on the temperature and pressure; see Figure 2. The higher the density of CO_2, the more efficiently the pore space can be used to sequester or store CO_2 as a separate phase. With an average geothermal gradient in the Netherlands of about 35°C/km, this critical point is reached at 600m. However, the hydrostatic pressure gradient of 10 MPa/km only allows safe storage at minimal 800m depth (van der Meer et al., 1992).

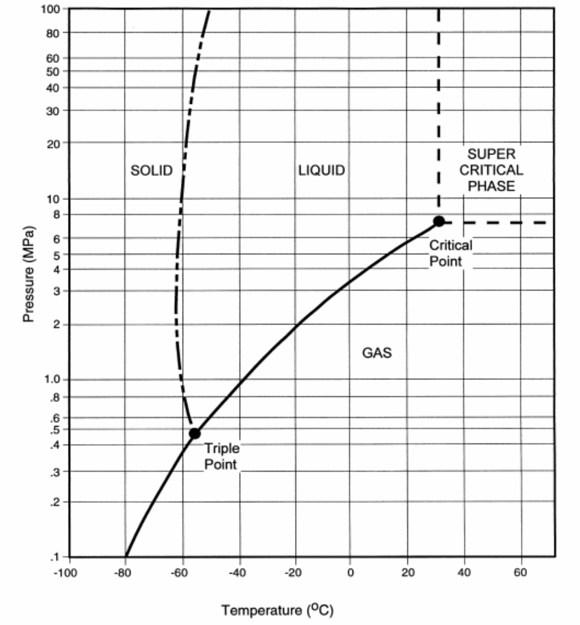

Figure 1 **Carbon dioxide phase diagram (Bachu, 2000)**

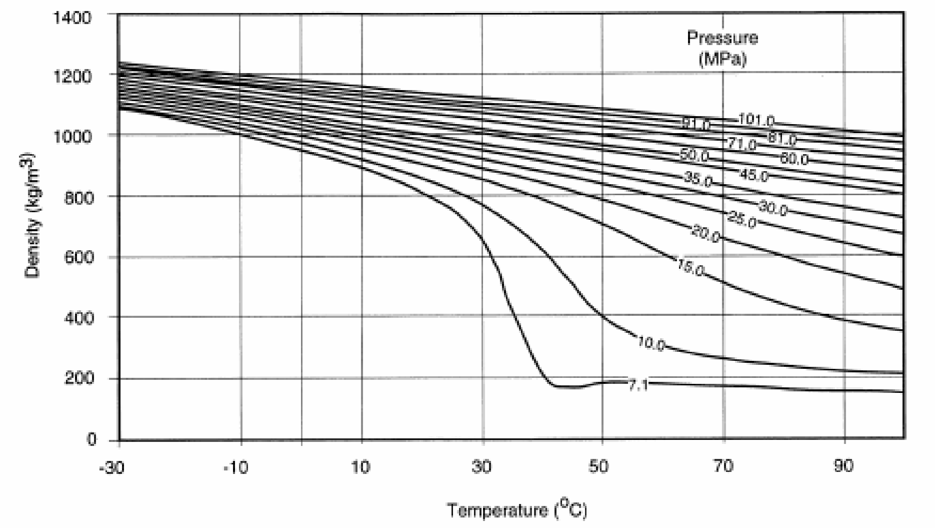

Figure 2 **Variation of liquid CO_2 density as a function of temperature and pressure (Bachu, 2000)**

2.1.2 Geological conditions

To physically store the CO_2 trapped in the underground, a geological trap must be present. This trap should be capable of capturing a certain volume gas or liquid in its porous reservoir. The geometry and the characteristics of the seals along all sides determine the trap. Seals could be impermeable rocks or faults that act as seal. Depending on the degree of a trap forming a sealing barrier to its environment for pressure communication and mass transport, a division of traps could be made in: closed traps, local open traps and regional open traps (Wildenborg, 1996).

The physical integrity of a seal includes the capacities to withhold pressure differences at injection, locally near the injection well, and during storage along the whole reservoir. The seal is a geological formation with appropriate hydraulic properties to effectively retain injected CO_2. Such seals (or cap rocks) will essentially be either shales, evaporates or most suitable lithology: rock salts (halite), which have a large capillary entry pressure and a low absolute permeability. Generally a seal performs better when it is thicker, highly homogeneous and compact. Anhydrite could erode due to CO_2 and interactions with dissolved CO_2 and clay minerals could lead to a decrease in porosity and permeability (Okamoto and Ohsumi, 2002). Faults could be sealing in some cases. As far as the sealing mechanism is based on smearing of the fault zone with clay, the sealing capacity could decrease when CO_2 is present.

The reservoir itself preferably has a sandstone lithology with minimal content of clay minerals. Sandstones have the highest permeability and preserve conversion of clay minerals and thereby possible congestion of the reservoir. Carbonate reservoirs are less suitable because of their possible dissolution which may arise when in contact with CO_2. Storage reservoirs also preferably have a high lateral continuity. Lateral discontinuity reduces the aerial extent of CO_2 from an injection point, so more injection wells are needed.

2.1.3 Storage mechanisms

Deposited, transported rock grains, organic materials and minerals after deposition form geological formations. In the pore space between the grains and in fractures a fluid is contained, which is mostly water with marginal occurrence of oil and gas. When CO_2 is injected into the pore space of permeable rock, it displaces the in situ fluid, dissolves or mixes with the fluid, reacts with the mineral grains or a combination of these mechanisms and affects the geological storage. The effectiveness of the geological CO_2 storage depends on its storage mechanism, which is a combination of geochemical and physical aspects. The ultimate goal of storage is to immobilize the CO_2. To inject CO_2 in the rock pores, four different storage mechanisms have been distinguished:

- Physical trapping; the most significant mechanism where CO_2 is injected in dome-shaped structures with cap rocks (stratigraphic and structural trapping) (Holloway, 1996). Structural traps are those formed by folded or fractured rocks. Stratigraphic traps are formed by changes in rock type caused by variations in the deposited setting. When there are not any closed structures CO_2 could displace the formation brine and be held in the pore space of the rock (hydrodynamic trapping). Fluid migrations are very slowly and over long distances. It remains under the sealing formation and on the longer term dissolves in the formation water.
- Solubility trapping; where CO_2 dissolves in the formation brine. This is thought to be a rather slow process. The occurrences of natural CO_2 accumulation pools, some of which are many millions years old, indicate that dissolution plays an insignificant role. Major benefit from solubility trapping is that once CO_2 is dissolved it does no longer exist as a separate phase and buoyant forces are eliminated.
- Mineral trapping; chemical reactions between the CO_2 and the rock minerals to form a solid mineral structure. This mechanism is the most permanent form of geological storage, but is believed to be relatively slow, potentially taking a thousand of years or longer.
- Residual gas trapping; CO_2 dissolves and becomes trapped in the water that remains in the pore space of the rock minerals (residual water) after formation water displacement by CO_2 (Senior et al, 2004). As the CO_2 migrates through the permeable formation, small droplets of supercritical CO_2 will also become trapped within the pore spaces by the surface tension between the formation water and the CO_2. This mechanism is also called phase trapping.

From model studies in the JOULE II report (Holloway, 1996) it seems that physical trapping is the most important storage mechanism during an injection process of several tens of years. The other three mechanisms are likely to be of a possible quantitative contribution on larger time scales.

2.2 Storage concepts

The options for deep underground CO_2 sequestration are show in Figure 3. Essentially geological carbon sequestration involves storing CO_2 in large natural reservoirs, or reservoirs that currently contain saltwater (deep saline aquifers), gas, oil or coal (hydrocarbon fields) or salt (salt caverns) for example. The first two options are the most promising options for CO_2 sequestration because of their big capacities. In the Netherlands the hydrocarbons fields are the most likely candidates for CO_2 storage (Table 1).

Table 1 CO_2 storage capacity in the Netherlands

Reservoir type	**Estimate of storage capacity (Mt CO_2)**
Deep saline traps (onshore)	600[1]
Oil and gas fields	11000[2]
Unminable coal seams	300-2900[3]

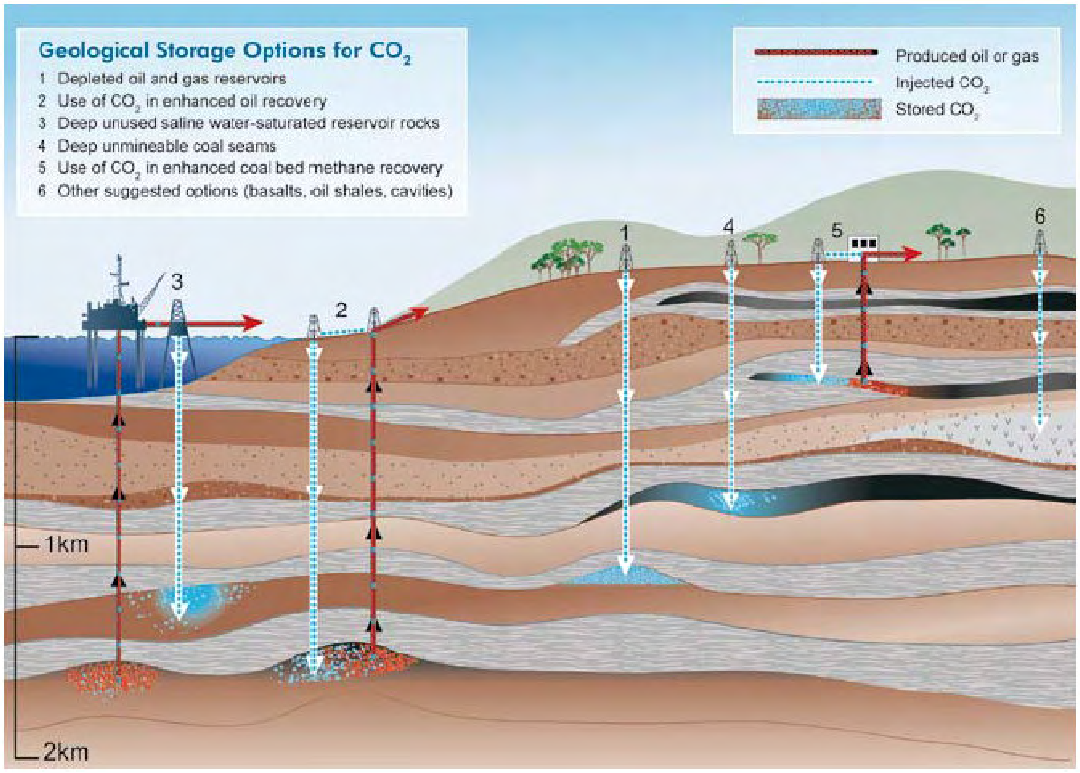

Figure 3 Options for storing CO_2 in deep underground formations (IPCC, 2005)

In the next section the most promising storage types are considered, namely depleted hydrocarbon structures (oil and gas fields) and deep saline formations (aquifer traps).

2.2.1 Depleted hydrocarbon structures

2.2.1.1 Definition

Hydrocarbon reservoirs consist of porous rocks covered by impermeable cap rock, and in a shape that will trap hydrocarbons. In essence, hydrocarbon structures are

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[1] TNO, in progress

[2] Wildenborg, 2003

[3] van Bergen & Wildenborg, 2002

aquifer structures from which the formation water is displaced by the hydrocarbons, because of their lower density. Hydrocarbons stored in the reservoir could be oil and/or gas.

For several reasons (nearly) depleted oil and gas fields are prime candidates for CO_2 storage. Following more than a century of intensive petroleum exploitation, thousands of oil and gas fields are approaching the ends of their economically productive lives (EIA, 2003). Depleted fields are effectively natural underground traps and have stored oil and gas over geological time scales, and so proved there integrity and safety. Some of these depleted fields could act as effective storage sites for CO_2. Other advantages of this option are small exploration costs due to existing infrastructure and there geological structure and physical properties are well known. Underground storage in natural reservoirs has been an integral part of the natural gas industry for many decades. Natural gas is routinely injected into, stored and withdrawn from hundreds of underground storage fields (see section 2.3.1). Major risk originating from CO_2 storage in depleted hydrocarbon fields are the wells penetrating the cap rock. Abandoned well plugs were never designed to withstand a buoyant and reactive fluid like CO_2 and deserve an assessment (Winter and Bergman, 1993).

In most oil fields only a portion of the original oil in place is recovered using standard petroleum extraction methods. CO_2 injected into suitable, depleted oil reservoirs can enhance oil recovery by typically 10-15% of the original oil in place in the reservoir (IEA, 2001). This is an established technique, called CO_2-EOR (enhanced oil recovery).

The same principle can be adapted to producing gas fields, referred to as CO_2-EGR (enhanced gas recovery). The prospect of EGR is more uncertain because it might result in lower gas recovery factors. However, disused gas fields do offer significant potential for CO_2 storage. Once gas has been extracted, the pressure within a field is reduced, providing an opportunity to inject CO_2, replacing the gas that has been extracted and maintaining pressure (USDOE, 1999).

2.2.1.2 Storage projects

Several pilot, demo and commercial storage projects have been undertaken in the past, are ongoing and are to be started in the future. In Canada the commercial Weyburn CO_2-EOR program started in 2000. In 20-25 years about 20 Mt CO_2 should be stored in this oil field, originated from a coal gasification plant (Moberg et al, 2003). The In Salah project in Algeria is also a commercial project where CO_2 re-injection takes place in a depleted hydrocarbon reservoir. From 2004 onwards about 17 Mt CO_2 from the Krechba gas field will be stored in a nearby sandstone reservoir at a depth of 1800 m (IPCC, 2005). In the Netherlands there is a CO_2-EGR demonstration project, leaded by TNO-NITG, where re-injection of CO_2 in an offshore gas reservoir at nearly 4000 meters depth takes place (van der Meer et al, 2005). The natural gas produced from the nearly depleted K12B gas field contains a relatively large amount of CO_2, which is now being re-injected in empty parts in stead of ventilated to the atmosphere. The total storage capacity will be approximately 8 Mt CO_2.

2.2.2 Deep saline formations

2.2.2.1 Definition

Deep saline formations are often referred to as (saline) aquifers. Aquifers are porous, subsurface rock layers containing salt water in the pores. This fossil, high salinity connate water is not fitted for industrial and agricultural use or for human consumption (Bachu, 2000).

The reservoirs seal is a geological barrier that isolate compartments within reservoirs or that hydraulically isolate reservoirs from each other. The seals may contain fluids but have very low permeability. From the petroleum industry also the term cap rock is used. Buoyant, migrating fluids remain trapped in the reservoir by the cap rock unless deformation or erosion breaches the seal.

Traps within the aquifer, like dome-like formation, might store CO_2. Following injection it will float to the ceiling of the dome (because CO_2 is less dense than the water in the aquifer) and will remain within it, prevented from any horizontal or lateral migration by the walls of the dome (cap rock).

The big difference between a hydrocarbon reservoir and an aquifer is that, in hydrocarbon reservoir, we know there is a seal. With an aquifer that is not necessarily the case. Moreover, not much effort has been put into delineate aquifers in the same detail that oil and gas reservoirs have been delineated. The immediate problems in aquifer formations are the significant uncertainties in the geometry, extent and flow properties (permeability distribution). Similar uncertainties pertain in characterization of oil and gas reservoirs, but much more information is available.

2.2.2.2 Storage projects

Less storage projects have been undertaken in deep saline formation. The Sleipner project in Norway is the first and started injecting in 1996. This offshore commercial project receives it CO_2 from a gas separation plant (Sleipner West Gas Field) and is injected in the Utsira Formation, 800 meters below the seabed of the North Sea. With a total storage of about 20 Mt CO_2 this is the biggest aquifer project under way. Some smaller projects are undertaken in the Frio pilot project (USA) and the Minami Nagoaka demo project (Japan) (IPCC, 2005).

2.3 Industrial and natural analogous

Industrial analogous to underground CO_2 storage provides sufficient information on the potential environmental consequences in these operations. Experiences come from the gas and oil industry and natural gas storage, but also from natural analogous such as Perrier in France where CO_2 naturally seeps out at the ground surface. For further reading Benson (2002) is suggested.

2.3.1 Natural gas storage

The underground storage of natural gas (UGS) is in this respect the most relevant comparison, since natural gas is just like CO_2 less dense than water and also migrates upwards due to buoyancy effects. UGS operations are successfully applied for over 100 years worldwide. They are used when peak loads and seasonal fluctuations cause imbalance in the gas network. Dutch gas storage fields are in Alkmaar, Grijpskerk and Norg. Mostly depleted gas and oil fields are used as storage facility, but also saline formations and salt caverns are used. Some accidents have taken place at these storage facilities, mainly caused by improper and poorly completed wells and leaking faults (Benson, 2003). Extensive monitoring is always part of ensuring storage safety.

2.3.2 Acid gas injection

Injection of acid gas (H_2S and CO_2) as an alternative for flaring is mainly practiced in Canada in the Alberta basin, where the gas is produced as a byproduct from sour hydrocarbon pools. It is injected into different reservoir types: 27 wells in deep saline formations, 19 wells in depleted hydrocarbon fields and 4 in an underlying water leg of those fields (Bachu and Haug, 2005). By the end of 2003 at total of 2.5 Mt CO_2 and 2 Mt H_2S had been injected in western Canada. Experiences and technologies from this type of injection can easily be applied for CO_2 storage, since a stream of CO_2 without H_2S is less corrosive and hazardous (Bachu, 2004).

2.3.3 Liquid waste injection

Very large quantities of liquid waste are injected in saline formations mainly in the US. The target contaminant groups for liquid waste injection are oil field brines, VOCs, SVOCs, fuels, explosives, and pesticides. The total annual injection rate in the US is about 3000 Mm^3. Experiences from this type of injection are a contribution to CO_2 storage as they operate at similar quantities. However, because CO_2 has a lower density and chemically and physically differs substantially from liquid waste, the use of this industrial analogue is rather limited (Benson, 2002).

2.3.4 Natural geological CO_2 accumulations

Accumulations of relatively pure CO_2 from geological setting, particularly in sedimentary basins, are found all over the world. Studying these reservoirs as natural analogous is relevant because CO_2 is trapped here for geological timescales. Studies have been undertaken on small scale CO_2 accumulations in Europe (Pearce, 2003) and Australia (Walton, 2004) and on larger scales in the United States, Europe and Australia (Pearce et al, 1996; Watson, 2004; Allis et al, 2001). Volcanic active systems are emitting CO_2 regularly, but are not representative as natural analogue because of different geological settings (active rather than stable) and their leaky character. Large quantities are emitted by for instance the Mammoth Mountain area (over 438.000 t CO_2 yr^{-1}) and the Kileaunu Volcano (4 Mt CO_2 yr^{-1}) (USGS, 2001). Famous example where large scale CO_2 emission led to fatal consequences is the seepage into and turnover of Lake Nyos (Cameroon) in 1987 (Kling et al, 1987). Exceptional circumstances like mentioned above are unlikely to be found at or near purpose designed CO_2 storage sites. Environmental impacts and damage resulted from such incidents do show that large scale seepage could have catastrophic results.

3 Risks associated with geological CO_2 storage

3.1 Risks

3.1.1 Definition

Risk is, at minimum, a two-dimensional concept involving the possibility of an adverse outcome and the uncertainty over the occurrence, timing or magnitude of that adverse outcome. If either attribute is absent, there is no risk (van der Sluis and Nieuwendorp, 2002). A formal definition is given by Covello and Merkhofer (1993): *'A characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown, and at least one of the possibilities is undesired'*. Risk is often defined as chance x outcome and could be qualitative as well as quantitative.

Risks associated with geological storage are broadly divided into two environmental impact categories; local and global risks. Global impacts arise from CO_2 leakage and thereby reduce the effectiveness of CO_2 storage. On a local scale there are several courses how stored CO_2 may pose a risk to health, safety and environment (HSE). As distinguished by Damen et al. (2003), there are five categories in which risks of underground CO_2 sequestration can be divided:

- CO_2 leakage: the loss of sequestered CO_2 from the storage reservoir to its environment.
- CH_4 leakage: the loss of CH_4 present in the storage reservoir due to CO_2 injection.
- Seismictivity: The occurrence of (micro) earth tremors due to CO_2 injection.
- Ground movement: Subsidence or uplift of the earth subsurface as a consequence of pressure changes induced by CO_2 injection.
- Displacement of brine: Flow of brine to other formations (possibly fresh water containing formations) caused by injection in open aquifers.

Risks are proportional to the magnitude and the probability. Where the hazard is a result of local elevated CO_2 concentrations, risks depends on the probability of the leakage from the reservoir. But two exceptions exist where risk is not proportional to the probability of release. First, spatial and temporal distributions of the fluxes and concentrations are the main factors that determine the local impacts. Acute and point leakage will likely have a bigger local impact than chronic and aerial leakage will have due to its dispersed character. Global impacts depend on the quantity released in the atmosphere over storage time scales. Secondly, impacts from e.g. ground movement are approximately independent of release probability.

In this study we focus only on risk of CO_2 leakage. This is the most significant risk posed by storage reservoirs in occurrence, magnitude and impact. For this reason only aspects considered with CO_2 leakage will be part of the assessment criteria.

3.2 CO_2 leakage

3.2.1 Definitions

The loss of stored CO_2 from a reservoir is separated in three different definitions (Chalaturnyk, 2005):

- *Migration*: refers to movement of CO_2 within the injection formation. This can involve movement both vertically and horizontally within the designated injection horizon where the fluids remain trapped by it seals.
- *Leakage*: refers to movement of CO_2 outside the injection formation through the geosphere. Such movement could be through the upper and lower bounding seals or through wells. After the movement outside the reservoir, there is a possibility for secondary trapping in shallower formation, or a flow path with a sufficient long travel time so as to meet the sequestration objective
- *Seepage*: refers to slow or diffuse movement of CO_2 from the geosphere to the biosphere, such as accumulating water bodies or ground surface.

Leakage from the target reservoir could occur in many ways, as illustrated in Figure 4:

- through faults and fractures (section 3.2.2),
- through poor quality or aging injection well completions (section 3.2.3),
- through the cap rock (section 3.2.4).

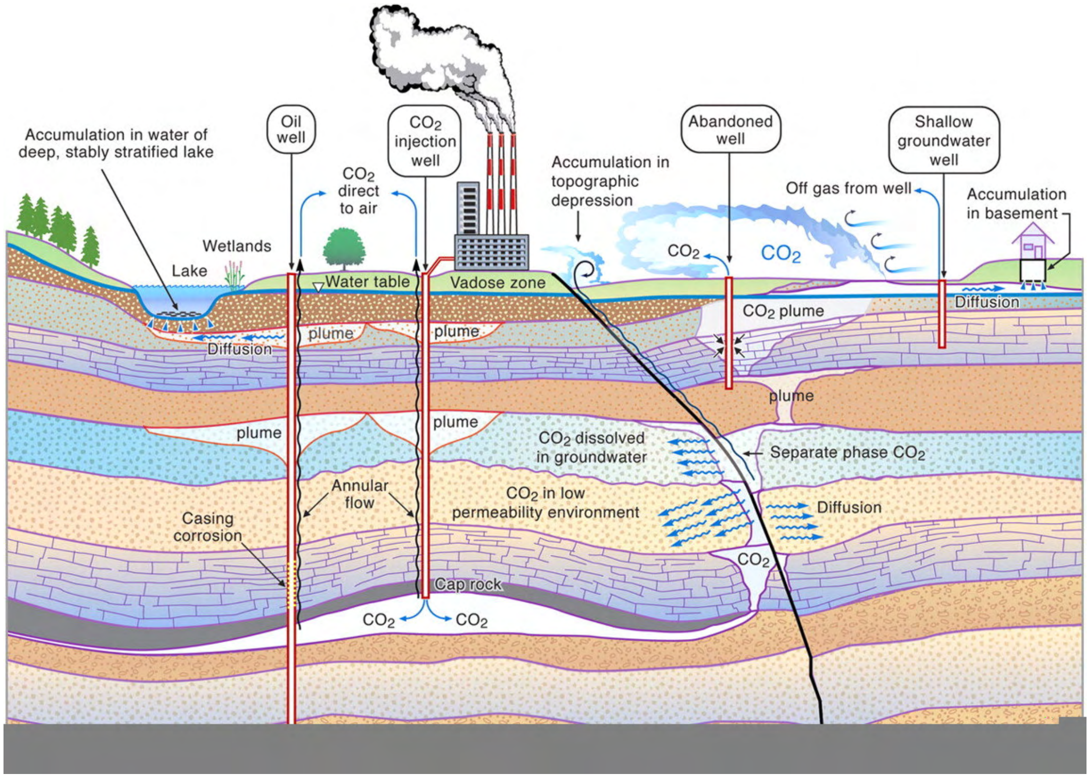

Figure 4 Conceptual model of potential leakage and seepage pathways and processes (Zhang et al., 2004)

3.2.2 Leakage through faults and fractures

CO_2 leakage through faults[4] and fractures[5] is considered as one of the most likely mechanism of all (Schulz et al, 2005). The vertical migration, or local linear leakage, might occur in a very short timeframe, of the order of years to tens of years or less (Celia and Bachu, 2003). Faults can act as barriers or conduits to fluid flow. The presence of hydrocarbon accumulations in the subsurface is often related to the sealing capacity of faults over geological time scales. Faults can therefore form an essential part of the bounding seal. Hydraulic integrity of the fault seal can be affected by mechanical, chemical and thermal forces (Schulz et al, 2005). In case of a (nearly) depleted hydrocarbon reservoir, the integrity is not only at risk during CO_2 injection and post abandonment, but also during initial exploration, development and production operations of the hydrocarbons. The behaviour of faults during CO_2 injection and subsequent storage is a critical issue not only in terms of seal integrity, also because of well failure. Fault reactivation could affect and damage well tubes.

Leakage from the reservoir via faults can occur in many ways:

- Leakage along faults,
- Reactivation of faults cutting through or bounding the storage formation,
- Shear failure of bedding planes in the cap rock,
- Reactivation of faults in the reservoir surrounding,
- Chemical degradation of fault sealing capacity / strength,
- Tectonic failure.

The sealing qualities of faults are especially important in reservoir boundary faults and faults that extend through the cap rock. Often, faults act as barriers to flow in sedimentary basins because of a very small maximum pore throat diameter. This may be the result from several different mechanisms such as cataclasis[6], clay smear[7] and diagenetic healing[8] (Jimenez & Chalaturnyk, 2002). Shear stresses along the reservoir-cap rock boundary as a result from horizontal reservoir expansion may lead to slip along bedding planes (Hawkens et al, 2004). Critically stressed and reactivated faults are also likely to leak (Streit and Watson, 2004). Fault leakage mechanisms are therefore not only related to the permeability (or sealing capacity) of faults, but also to an interplay of fault geometry, in-situ tectonic stress field, and stress development induced by CO_2 injection and eventually by reservoir exploitation. Stress arching[9] related to contrasts in rock stiffness and pore pressures can alter the in-situ stress field near faults significantly, eventually supporting the reactivation of faults (Mulders, 2003). Chemical reactions between the fault gouge material and CO_2 could affect the fault sealing integrity. Tectonic activity near geological storage reservoir is always unacceptable.

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[4] break or planar surface of brittle rock across which there is observable displacement
[5] crack or surface of breakage within the rock along which there has been no movement
[6] reduction of grain size to a type of metamorphic rock
[7] injection of clay into a fault by deformation of shale (-rich sandstones) along the fault
[8] alteration of sediments into sedimentary rock
[9] shedding the overburden load to the edges of a reservoir that undergoes compaction

3.2.3 Leakage through wells

Exploration and production wells have been drilled for about a century, which means that multiple wells are to be found in depleted oil/gas reservoirs and could be in the vicinity of the storage reservoir. Because some of them are in bad condition (Veloski and Hammack, 2006), abandoned wells form an important migration pathway (Gasda et al, 2004; Benson, 2004). Especially unidentified and poorly abandoned wells are potential point sources. Because free-phase CO_2 is lighter than the formation brine, the potential for upward leakage is enhanced by buoyant forces. Well leakage causes a local point leakage, where high concentrations and fluxes may evolve because of the direct connection between the storage reservoir and the surface.

According to Holloway et al. (1996), the major risk associated with injection is a wellhead failure, which could be caused by unsuitable construction and execution, leaking pipe connections, defective materials and collapse of the well. Such a catastrophic accident would cause an acute leakage of CO_2. As does a well blowout, which is unlikely to occur (Holloway, 1996) with leakage quantities only equal to the tube content. Clark (1999) concluded that the most probable failure mode may be attributed to cement micro-annulus leaks, and the injection tubing leaks least. Events like this would cause slow leakage.

Possible leakage pathways along an existing well are shown schematically in Figure 5. It includes possible preferential flow pathways along the rock-cement interface, along the casing-cement interface, and through degraded materials. Because well-formed cement has very low permeability, on the order of 10^{-20} m^2 (10^{-5} mD) (Gasda, 2004), no significant flow of CO_2 can occur unless there are preferential flow paths, or the material has degraded due to CO_2/brine interactions or not formed properly during the emplacement process. Formation water with dissolved CO_2 may, when reaching these wells, enhance and speed up the cement degradation, leading to possible leaks through the well annulus[10] and/or along casing (Bachu and Gunter, 2003). New cements are being developed as alternative for the Portland cement. These CO_2 proof cements will maintain low porosities during CO_2/brine contact.

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[10] space between casing and tubing

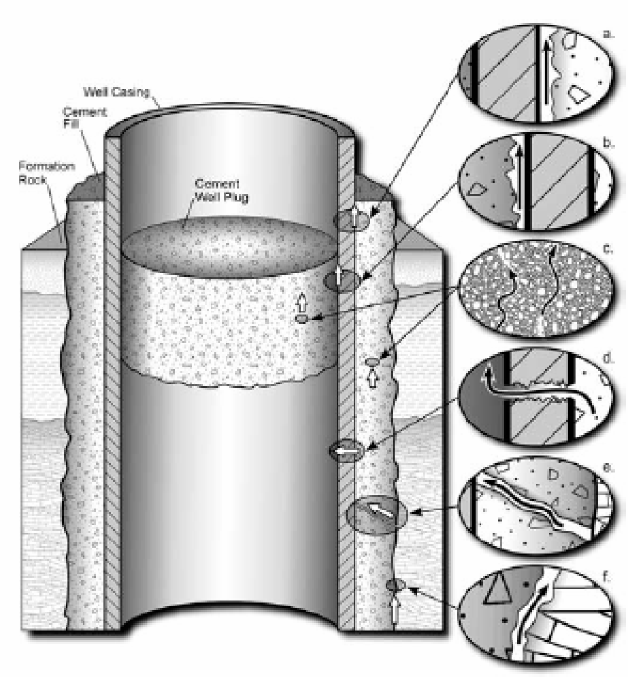


Figure 5 Potential leakage pathways along an existing well: between cement and casing (a&b), through the cement (c), through the casing (d), through fractures (e) and between cement and formation (Celia et al, 2004)

Diffusion of CO_2 through the cement caused by corrosion is a process, which will progress very slowly at approximate rates of 20 cm in 100 years (Seinen et al., 1994). However, it is uncertain how the well bore integrity is affected by CO_2 and brine considering a long sequestration timescale. Existing wells may serve as preferential leakage pathways over time scales of ten to hundreds, even thousand years and may therefore represent a significant (long-term) risk (Celia and Bachu, 2003). Short-term relevant experiences were made regarding the cement compatibility with acid gas and showed that a non-carbonate and calcium cement blend shattered during tests for several weeks (Bachu and Gunter, 2003).

3.2.4 Leakage through cap rock

The injection of CO_2 will stimulate a variety of coupled physical and chemical processes, which may affect the hydraulic integrity of cap rocks and could cause diffuse areal leakage. Up to now, research and investigation has primarily been conducted into the properties of seals, especially within the context of hydrocarbon migration and traps, and focused on geological processes. The existence of hydrocarbon reservoirs, especially gas reservoirs, is commonly offered as evidence of the suitability of a particular cap rock for containing CO_2 injected. For large-scale geological storage projects, however, CO_2 injection may alter the in situ characteristics of these cap rocks, possibly degrading its sealing properties. Knowledge of how those properties evolve is however weak. Therefore it is necessary to understand how bounding seals will react under pre- and post-operational conditions, with a focus on hydraulic integrity over both the short-term and long-term (Schulz et al, 2005). The bounding seals and their surroundings can also be affected by CO_2 injection. Among the most notable are changes to the stress field due to pore pressure and temperature changes, immiscible displacement of one of the phases by CO_2, partial dissolution of CO_2 into the aqueous phase, and chemical interactions between the CO_2 and the aquifer and cap rock. Therefore, permeability is affected by these changes, resulting in changes in the hydraulic integrity of cap rocks during the lifetime of the project. It is expected that these changes will be most prominent during the short-term (injection stages) (Jimenez & Chalaturnyk, 2002).

3.3 Impacts

This includes the impacts of a leakage event or process to people's life and health and to the vadose zone onshore and the marine environment offshore. The impacts of leaked CO_2 can be evaluated at two different levels:

- local, and
- global.

3.3.1 Local impacts

When seepage of CO_2 happens (stagnant pooling), regional consequences will occur close to the source of the migration route. Exposed to elevated concentrations could lead to health effects to humans and animals and negatively influences the ecosystems. These effects depend on the concentration and duration of exposure time (Benson, 2002). The effects on humans are given in Table 2.

Table 2 Health effects on humans (Benson, 2002)

Concentration CO_2	**Health effects**
<1 % (10,000 ppm)	No physiological effects.
1-3 %	Physiological adaptation occurs, without adverse consequences.
3-5 %	Significant effect on respiratory rate and some discomfort.
5-10 %	Physical and mental ability is impaired and loss of consciousness can occur.
>10 %	Rapid loss of consciousness, possible coma or death.

Other air-breathing animals have a similar tolerance to CO_2 as humans so that concentrations up to 20-30% will kill all forms of life other than microbes, invertebrates and insects (Benson, 2002). Plants, insects, and soil organisms have a higher tolerance to CO_2 than most other life forms. Moderate increases in CO_2 concentrations may stimulate plant growth as a fertilizer, but large volumes of CO_2 may cause localized toxic concentrations in the soil. Soil gas CO_2 concentrations of 20-30% may result in root damage and plant demise and cause die off of vegetation. For example, extensive areas of tree-kill have occurred at Mammoth Mountain, USA due to volcanic out-gassing of CO_2 since 1990 (McGee and Gerlach, 1998). When CO_2 reached a drink water source reservoir, it lowers the pH. It can immobilize metals that are otherwise harmlessly bound in minerals in the aquifer reservoir rock and so contaminate fresh water.

For an offshore stagnant pooling at the sea bed floor the situation is different. At depths of about 2800 meters and deeper CO_2 is denser than sea water and will not rise but pool on the sea floor. At shallower depths the CO_2 will rise and disperse quickly, probably dissolved before reaching the atmosphere. Consequences for the marine life are likely to be negligible, although this should be confirmed. Pooling on the other hand is expected to be toxic for marine life (Kita and Ohsumi, 2004).

3.3.2 Global impacts

When the leaked CO_2 reaches the atmospheric level it reduces the benefit of storing it in the first place (reduction of CO_2 storage as effective mitigation option) and can pose higher risks with increasing concentrations. Regarding climate change mitigation, a maximum leakage rate of approximately 0.001-0.01% per annum of stored CO_2 per annum has been suggested as being acceptable, taking into account possible scenarios for future CO_2 emissions through fossil fuel usage (Benson and Hepple, 2005; Pacala, 2003; Hawkins, 2003). From an economic perspective this is agreed by Dooley and Wise (2002). A leakage rate of 0.01% per year would ensure that 90% of the carbon dioxide would remain underground over a 1000 year time period (Benson and Hepple, 2005). Leakage rates of more than 1% annually are unacceptable. They imply that most of any stored carbon dioxide would return to the atmosphere after only 400 years (Benson and Hepple, 2005). In any case, leakages should not cause worse climatic conditions in the future than is to be expected in the case of direct emissions.

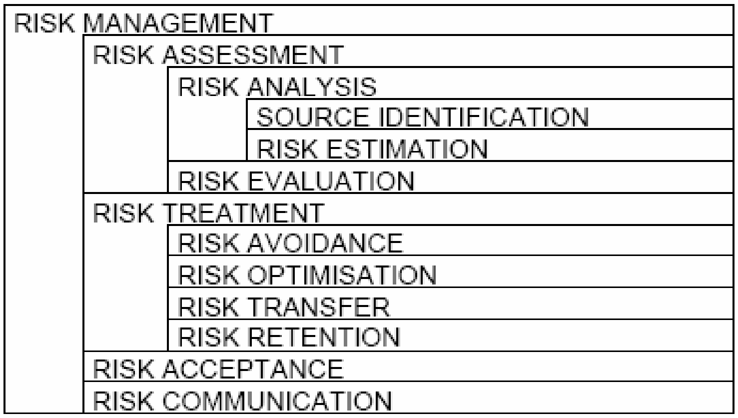
Offshore waters can be contaminated with CO_2 by seafloor seepage and solution at the atmosphere/ocean interface. Coral reefs, calcareous plankton and other organisms whose skeletons or shells contain calcium carbonate may be particularly affected. Most biotic species reside near the ocean floor, where the biggest pH changes expected to occur (Caldeira and Wickett, 2002). A decrease in production of biological material at the bottom of the marine food chain could lead to disastrous effects on entire ecosystems in large parts of the ocean.

4 Risk assessment framework and methods

This chapter consists of two main parts. The first part is concerned with reviewing risk assessment in its broader context (§4.1) and different types of risk assessments (§4.2).
The second part of this chapter is concerned with the development of two different conceptual frameworks we applied. A MAUT approach (§4.3) was first employed. When it proved to have several drawbacks a more formalized and holistic manner of assessment was feasible, for which fuzzy logic might be a solution (§4.4). A consideration of risk assessment methods gives a short overview (§4.5).

4.1 Risk assessment

A risk assessment is treated as an integral part of the all-embracing risk management process which encompasses the assessment, treatment, acceptance and communication of risks (Figure 6). Risk assessment is an appraisal of both the kinds and degrees of the threat posed. Such appraisal includes the recognition of the hazard, the measurements of its threat and understanding the (social, economical) meaning of such measurements. The elements of risk assessment are not rigidly separate categories of endeavor, they overlap considerably (Kates, 1978). Rather than a linear process, risk assessments are generally cyclical and iterative by nature. Source identification is the recognition of a hazard, answering the question: what constitutes a threat? Methods to identify threats are e.g. research, screening and monitoring. Risk estimation is the measurement of the potential threat, answering questions like: how great are the consequences and how often do they occur? Methods are e.g. historical, experiment data extrapolation and modeling. Risk evaluation is the meaning attributed to the measurement of threat potential, answering: how important is the estimated risk? This can be done by e.g. cost-benefit analysis.



- RISK MANAGEMENT
  - RISK ASSESSMENT
    - RISK ANALYSIS
      - SOURCE IDENTIFICATION
      - RISK ESTIMATION
    - RISK EVALUATION
  - RISK TREATMENT
    - RISK AVOIDANCE
    - RISK OPTIMISATION
    - RISK TRANSFER
    - RISK RETENTION
  - RISK ACCEPTANCE
  - RISK COMMUNICATION

Figure 6 Relation between different disciplines of risk management (TMB&ISO Standards, 2002)

The identification of assessment criteria is a starting point how data and knowledge can be employed as evidence for measuring potential adverse impacts. Next questions about what and how it might happen and the likeliness and seriousness are used to assess the risks. A combination of hazard identification, consequence and likelihood assessment leads to a qualitative or quantitative estimate of the level of risk.

4.2 Risk assessment methodologies

A key activity in risk assessment projects is to develop methodologies and tools to evaluate HSE risks and to develop monitoring tools that allow for early detection and remediation. Risk assessments themselves aim at identifying and quantifying potential risks originating from subsurface CO_2 storage. Because CO_2 storage is a rather young study area, new methods are being proposed and no well established method for this purpose exists. However, many applied methods and models are originally developed in the oil and gas industry. Depending on project complexity, project phase and uncertainties, there are generally three different types of risk assessments: deterministic (DRA), probabilistic (PRA) and qualitative studies. In this section a brief overview of existing assessment methods to evaluate long term risks are presented.

4.2.1 Deterministic risk assessment

Deterministic Risk Assessments (DRA) only consider one fixed and time independent input value for each parameter in the model to calculate the consequences. They are based on best estimates and most likely system parameters. Therefore it can not deal with the parameter uncertainty and the results are consequently highly uncertain. To have valid results, often conservative values are used, to overestimate the resulting risks. This again introduces problems, where relationships between the parameter value and the risk may not be monotonic and overestimated results are highly unlikely (Wildenborg, 2003). DRA is useful in determining trends due to single parameter variation (sensitivity analysis) or best/worst case scenarios. It gives very accurate results if the input parameters are known exactly. Exhaustive stochastic analyses with DRA resemble probabilistic risk assessments (section 4.2.2).

A deterministic approach (as well as a probabilistic) was applied in the IEA GHG Weyburn Project, both to assess geosphere migration of CO_2 and a single well performance (Walton et al, 2004). It was found that the primary variability in the geosphere model is the heterogeneities in CO_2 distributions and rock properties in the reservoir. As for the abandoned wells, their variability of characteristics necessitated a stochastic approach.

4.2.2 Probabilistic risk assessment

The most preferable manner of assessing long-term risks in complex systems is probabilistic, to treat uncertainty explicitly. Probability Risk Assessment (PRA) can statistically quantify the uncertainty associated with the parameters describing the processes in the deterministic models. In deterministic models with only one input value for each parameter, only one outcome is realized. By using PRA models a range of input values (eg PDF/probability density function) for each input parameter gives a range of outcomes. A PDF could have numerous distributions (e.g. triangular, normal, lognormal), describing the uncertainty or variability of the input parameter. Producing PDFs could be done by using Monte Carlo analysis, directly be derived

from measured data or may be assigned by expert judgments (Morgan and Henrion, 1999). PRA provides a holistic assessment of the uncertainty associated with CO_2 storage. Disadvantage for our purpose is that this method relies on accurate PDFs and will be more suitable for site specific research.
A probabilistic approach to assess the performance and risk of geological CO2 storage has been carried out in the Weyburn project (Walton et al, 2004), as well as the SAMCARDS project (Wildenborg, 2003). Leakage fluxes and concentrations in the geosphere were quantified for a leaking fault and a leaking well scenario. The scenarios were analyzed with coupled physico-mathematical consequence models in a probabilistic manner. Because of limitation to the computational power and since PRA's take a lot of processing time the models were simplified. PRA showed that CO_2 concentrations and fluxes in the biosphere were largest in the case of a leaking well as compared to the leaking fault. However, the time span of release of CO_2 to the biosphere was larger in case of the leaking fault.

4.2.3 Qualitative risk assessment

Often, it is inappropriate to perform an in-depth quantitative risk assessment (like DRA and PRA), and qualitative risk assessment may be sufficient and more effective. This more subjective approach (often based on qualitative data) can be employed when there is a lack of data and/or specified knowledge, time and expertise. Consequently, qualitative risk assessment does not provide concrete, numerical results but relative or qualitative results.

4.2.3.1 FEP analysis

Within this approach, scenarios which could cause HSE impacts are being constructed, based upon a FEP analysis (feature, event, process). FEPs are all relevant factors that describe the current state and possible future evolution of a project (Wildenborg, 2003). In this context, features include a list of parameters, such as cap rock porosity, number of wells and reservoir permeability. Events are processes like seismic events and well-blowouts. Processes are physical and chemical processes such as geomechanical or geochemical processes and multi-phase flow behaviour. Figure 7 illustrates the different stages in a FEP analysis, from FEP identification to scenario formation.
The original approach is developed for different kinds of underground exploitation, especially underground storage of nuclear waste. The methodology aims at a complete description of the possible state and future behaviour of the underground facility and its surrounding environment based on a rigorous inventory of FEPs that are relevant to HSE, resulting in a comprehensive list of FEPs (Maul, 2003). The analysis can be employed in two ways, bottom-up or top-down. The bottom-up approach uses the database directly to develop the assessment models. In the top-down approach the database is used as audit tool to ensure all relevant FEPs are included in the models and to document why others have not been considered (Maul, 2003).
In the first stage a team of experts evaluates the FEP database and rank them according to both qualitative and quantitative descriptions of their probability of occurrence and their possible impact. After dividing them in base case FEPs and

scenario defining FEPs, the scenario defining FEPs with similar effects are grouped to reduce their numbers and to lower the number of variant scenarios.
The FEP analysis is useful in the licensing and certification stages of project development. It provides a complete qualitative risk assessment of plausible scenarios in a short period of time. A disadvantage of the FEP analysis for early site selection is that it is a diligent and time consuming method which requires considerable site specific information to provide sufficient site specific scenarios.

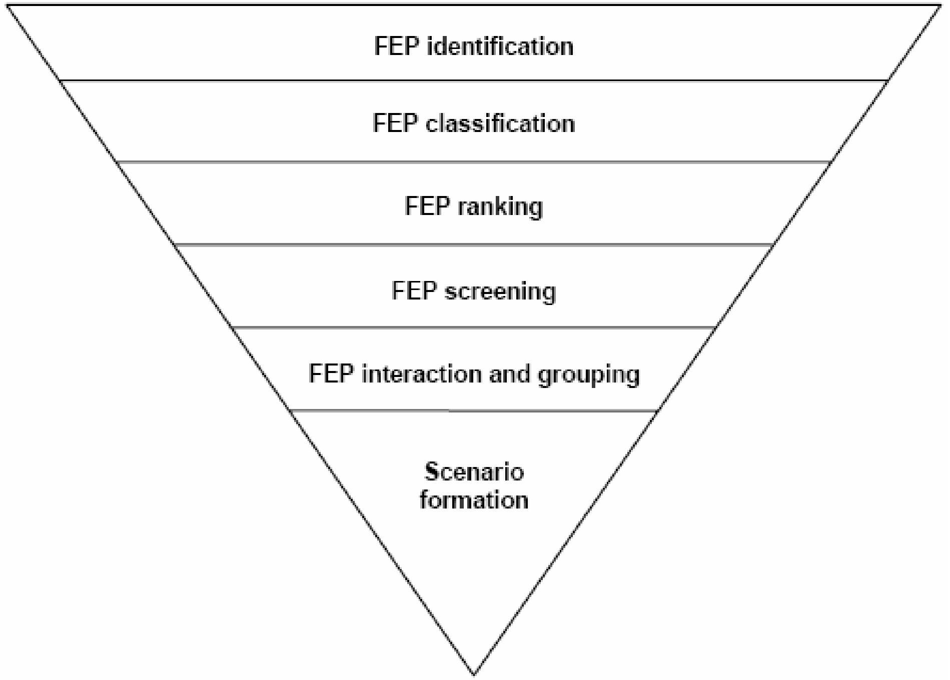


Figure 7 **Scheme of stages in the FEP analysis (TNO, 2003)**

The development of databases for evaluating risks by means of a FEP analysis scenario approach has been done by two organizations (TNO-NITG and Quintessa). Because the databases were developed for different purposes they structurally differ. Within the SAMCARDS project, leaded by TNO-NITG, several workshops with international experts resulted in a database containing over 600 FEPs at the moment. This database was applied to two imaginary reservoirs and recently in the Schweinrich project. The aim of the database was to development a tool for assessing risk. Scenarios of a leaking fault and a leaking well were acknowledged to be the most likely (Wildenborg, 2003), after which a PRA was applied. The Quintessa database was developed only for the Weyburn case and therefore contained less (some 200 FEPs), and used as an audit tool for checking the completeness of the DRA/PRA models. It was successfully applied in the Weyburn Project.

4.2.3.2 MAUT

Based on the multi attribute utility theory (MAUT), which will be more extensively discussed in section 4.3, Oldenburg (2005) developed a screening and ranking framework to evaluate potential CO_2 storage sites on the basis of HSE risk arising from possible CO_2 leakage. The results of comparison can be used to select the best

CO_2 storage sites for detailed risk assessment from a selection of sites. In this approach no modeling or simulation nor probabilities are assigned, to make it as simple and transparent as possible and applicable in that stage where only limited data is available.

It is assumed that HSE impact is related to three fundamental site characteristics:

- Potential of the target formation of long term CO_2 containment,
- Potential for secondary containment due to leakage of the primary site, and
- Potential of attenuation and dispersed leakage in case both fail.

These site characteristics are divided into attributes which describe the state of that particular characteristic (e.g. the attributes primary seal, depth and reservoir describe the potential of the target formation of long term CO_2 containment). All attributes are than assessed with site specific information by an expert who indicates the relative importance (weight factor), a level of risk contribution and a degree of confidence. An aggregation of a weight factor, contribution to risk and confidence gives the reservoir a semi quantitative score with respect to the posed HSE risks. The method provides a qualitative and independent assessment of these three characteristic through an evaluation of its properties. The resulting site scores from the assessment are representative for the relative scoring without indicating an absolute site performance (Oldenburg, 2005). Applications of the framework to the Rio Vesta gas field, Ventura oil field and Mammoth Mountain demonstrates the applicability of the approach.

A weakness in the way Oldenburg uses MAUT is the arbitrarily assigning of weight factors and confidence scores and confidence not being defined. Strong points are its transparency, simplicity and the ease to extend when new knowledge or data is available.

4.2.3.3 SWIFT

A SWIFT (structured-what-if technique) method was applied to analyze the risks of geological formation, conducted by Det Norsk Veritas (Vendrig, 2005). With questions like “What if…?” and “How could…?” SWIFT is a systematic team-oriented technique for hazard identification. The aim was to make a qualitative estimate of risks and to ensure the experts involved have a good common understanding. Its objectives were

- To identify hazards that may result in leaks of CO_2 from various possible types of geological structures and the safeguards that are planned to minimize the risks.
- To evaluate the likelihood and consequence of CO_2 leaks by comparing the hazards and safeguards to those present in conventional natural gas production (and, if possible, injection and storage).
- To evaluate the relative importance of the different hazards in contributing to the total expected quantity of CO_2 leaking during the reservoir life.

The SWIFT was than extended into a Delphi exercise. The purpose here was to quantify the likelihood and size of accidental releases from different types of geological reservoirs, fed with quantitative geological data.

It was concluded that the majority of the experts retained the view that it is currently impossible to make any reliable quantitative estimates for CO_2 sequestration. Further research, combined with site specific experiences could maybe permit quantitative estimates in the future. For site classification this method is not useful, where we want to formalize expert knowledge and develop a repeatable and structured framework.

4.2.3.4 RISQUE

A combined approach has been undertaken in the Australian GEODISC (Geological Disposal of Carbon Dioxide) program (Bowden and Rigg, 2004). The RISQUE method (Risk Identification and Strategy using Quantitative Evaluation) is a systematic, quantitative process that uses a formal group of experts to provide judgments that are incorporated into a quantitative risk analysis and management framework. By using an event-tree approach, for each site specific identified risk event a probability, consequence and time scale of occurrence should be given. In essence the list of risk events can be interpreted as a FEP list. The aim of the exercise was to rank the suitability of four deep saline aquifers as potential demonstration projects. The risk factors assigned were much broader than geological risk considering project financing and wider community benefits as well. A containment and effectiveness risk score formed aggregated results. For the same reasons as a FEP analysis this approach is less suitable for our case. Also the broadness of assessment criteria falls out of our scope.

4.3 Multi Attribute Utility Theory

4.3.1 Rationale

From the previous section it proved that a quantitative analysis is not feasible for discriminating between sequestration sites, where there is a lack of detailed research and most of all (historical) field data. A study to quantify leakage risk, done by Vendrig et al. (2005), also concluded that it is currently impossible to quantify with any confidence the likelihood of accidental releases from CO_2 storage reservoirs. This is a plea for a more qualitative approach. Instead of modeling the leakage fluxes, a qualitative or semi-quantitative notion of the leakage risk of a site, based on specific geological characteristics and knowledge base uncertainty would be a more suitable approach. A multi attribute utility theory (MAUT) approach is chosen because of its suitability to score and rank alternatives based on structural system decomposition and the possibility to introduce expert knowledge. It presents the evaluation and decision process in a transparent way. With a decision analysis approach based on MAUT (Keeney and Raiffa, 1976), a form of multi criteria analyses (MCA), a suitable tool is at hand to evaluate alternatives when no salient, agreed-on evaluation criteria are available. Knowledge integration in MAUT is organized in multiple ways, such as linking the system knowledge to the evaluation criteria and by integrating attributes from different compartments and disciplines. MAUT also supports the analysis of a decision situation, makes them transparent and comprehensible. The objective of MAUT is to attain a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives. Thus, the method is recommended when alternatives must be evaluated to determine which alternative performs best. The main difference between MAUT and MCA is that MAUT assumes a dependency of preference, enabling the inclusion of subjective elements (utility functions), whereas an MCA has fixed preferences.

The evaluation process encompasses both analytical decomposition and synthesis. MAUT decomposes the overall attractiveness of an alternative into a number of attributes (von Winterfeldt & Edwards, 1986). Attributes are preference related dimensions of a system, for which a utility measurement is constructed. The attractiveness of an alternative with respect to an attribute is measured by means of a utility function, which makes utility the quantitative operationalization of the evaluators' preferences. Then trade-offs among attributes are quantified as importance weights, which ideally correspond to the evaluators values. If alternatives have been rated according to all the attributes, MAUT composes the ratings and organizes a synthesis resulting in a one-dimensional utility measure (Scholz & Tietje, 2002). A schematic representation of the MAUT method is seen in Figure 8.

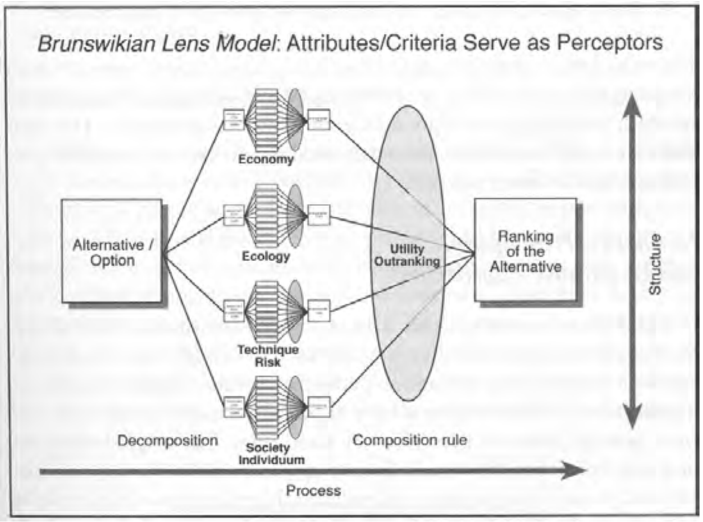


Figure 8 **Schematic representation of the multi-attribute utility theory (Scholz&Tietje, 2002)**

The theory is well developed and tested for many years and has scientific and axiomatic foundation (e.g. Keeney and Raiffa, 1976 and Winterfeldt & Edwards, 1986). Because most public sector problems involve multiple conflicting objectives, such as in public health care systems (Lathrop & Watson, 1982), environmental policy (Ulvila & Snyder, 1980) and site selection (Kirkwood, 1982), the opportunities for MAUT applications are apparent and numerous.

4.3.2 Application of MAUT to screen and rank geological CO_2 storage sites

The decomposition is based upon evaluation criteria that affect the leakage of CO_2 (Table 3). It follows the concept of a hierarchy in leakage concerns through different attributes of a site. Attributes that have an approximated similar HSE impact when they fail are grouped in a concern. This differs from Oldenburg (2005), where attributes are grouped that influence one of the fundamental characteristics he defined (see section 4.2.3.2).

The assessment made in the framework is based on four classes of information: (1) leakage concerns, which are defined by (2) site attributes, which are defined by (3) properties which are defined by (4) values. For example, the primary *leakage concern* has two *attributes* (wells and faults). The attribute 'wells' has two *properties*, namely wells density and well drill date and the attribute 'faults' has two *properties*, namely fault density and seismic risk. These four properties are proxies for the well quality, the likelihood of direct well and fault pathways to the surface and fault reactivation potential. Of primary concern are the most obvious leakage pathways; through wells and faults. Both could possibly act as direct pathways from the storage reservoir to the surrounding environment or surface. Although faults could act as barriers, they are regarded as a potential leakage path when the sealing capacity of a fault is unknown. This is likely to be the far most important category in storage site risk assessment. Of less concern (and so secondary) is the primary seal, of which failure is most likely to be dependent on attributes from primary concern and reservoir characteristics. Also of less concern are the tertiary ones which influence leakage risk only marginally. For instance: the reservoir may influence leakage due to increased areal extent because of a small thickness, and reservoir depth influences the CO_2 phase behaviour. The secondary seal is a potential for secondary containment in case the primary target site leaks. The overburden is descriptive for the dispersed character of the leakage. Appendix 1 describes the properties in detail.

Table 3 Concerns, attributes, properties and proxies (adapted from Oldenburg, 2005)

Concern	Attribute	Properties	Proxy for	Unit
Primary	Wells	well drill date	likelihood well quality	-
		well density	likelihood direct well pathways	nr/Mt CO_2
	Faults	fault density	likelihood direct fault pathways	m^2/m^2
		seismic risk	reactivation faults	-
Secondary	Primary seal	effective porosity	likely sealing effectiveness	%
		thickness	likely sealing effectiveness	m
		heterogeneity	vertical connectivity	-
		demonstrated sealing	leakage potential	-
Tertiary	Reservoir	effective porosity	capacity	%
		thickness	areal extent of injected plume	m
		permeability	injectivity	mDarcy
		depth	density of CO_2	m
		heterogeneity	vertical connectivity	-
	Secondary seal	effective porosity	likely sealing effectiveness	%
		thickness	likely sealing effectiveness	m
		depth	density of CO_2	m
		heterogeneity	vertical connectivity	-
	Overburden	thickness	likely sealing effectiveness	m
		transmissivity	likely CO_2 dispersion/dissolution	m^2/day

Obviously, there are other properties that also affect the performance of the storage reservoir, such as seal and fault permeability and reservoir pressure. It was not possible to include these properties in the framework because there was not sufficient data to make sound conclusions.

For each attribute property a utility function is to be constructed. This is the second difference with Oldenburg (2005), where he does not include predefined utility functions. The utility function here is a measure of tendency for leakage risk posed by the property being assessed, while injecting a maximum amount of CO_2. For example, a reservoir without any wells has no risk from the well attribute, which gives zero wells a utility of 1 (on a scale from 0 to 1). The more wells penetrate the reservoir, the more leakage risk they cumulative pose. The utility function here is the type of curve (e.g. linear, concave) which describes the relation between the property universe of discourse and its utility. Obtaining the utility functions is based on expert judgment. A selection of experts from different geo-scientific institutes was made. The consultancy is conducted by email because of practical reasons and to allow for reflection time (Appendix 2). A second consultancy round would acquire weight factors to emphasize disproportional contributions of attributes properties to leakage risk.

We believe that only a utility measurement is thought not to be a sufficient measure for the leakage risk of a storage site. Rather than one dimensional, scoring and ranking sites based on leakage risk should be seen as a two dimensional measurement, including both a utility and an uncertainty measurement. An extension of the MAUT approach with an uncertainty assessment (e.g. NUSAP (van der Sluijs, 2005)) may give more insight in the risks posed. The two separate risk and uncertainty scores together form a final site score. The metrics for risk contribution and uncertainty per storage site could be combined in a diagnostic diagram.

4.3.3 Conclusions

The whole evaluation process relies on expert judgments, for which a consultancy was necessary. The questionnaire was filled in by four experts from different institutes, all of them being geologists. An advantageous outcome was that the questionnaire showed largely comparative results for the utility measurement and the property value hierarchy. They fitted the same utility curve for most of the properties and gave almost similar hierarchies, indicating a high degree of consensus. However, a complete development of the method never took place, because the manner in which MAUT was applied here had a methodological drawback concerning the usability of utility measurement.

With a utility measurement the property value is to be converted directly by interpolating the utility curve to a degree of leakage risk. A summation of separate property leakage risks degrees would constitute for the overall attribute degree of leakage risk. Leakage processes are not solely dependant upon only one of the properties, but a combination of them. By scoring properties separately one would disregard the mutual interaction between them and thereby the interpretation and complexity of the system. Reciprocal behaviour of properties within their attribute is to be descriptive for a possible leakage risk and cannot be implemented within the current framework.

A cautious treatment of the knowledge with respect to risk is necessary. The full dependency on non repeatable and intuitive expert knowledge, which coincides with a high degree of uncertainty since the risk processes are not well understood without strong knowledge, makes the outcomes not robust. Complexity and casual interactions cannot be ignored. A more formalized and holistic manner of assessment is feasible, where fuzzy logic might be a solution.

4.4 Fuzzy logic

4.4.1 Rationale

Experienced geologists are able to provide insight in complex geological systems without detailed knowledge of the system at hand. This makes it possible to assess risks at some rudimentary level based on available data and an expert opinion. When consulted systematically on the importance of several reservoir characteristics and assessed according to a proper framework, reservoirs could be compared on their relative leakage risk. However, experts mostly present their solutions in linguistic terms, which imply a high level of abstraction as for example:

If the primary seal thickness is *small* and its porosity *high* then the chance of a (diffused areal) leakage process through this seal to occur is *high*. The terms in italic in the propositions are fuzzy by nature. In other words, a unique definition does not exist and they are problem dependent. These terms can be represented using fuzzy set theory (Zadeh, 1965) and the concatenation of the ideas can be formulated using rule based fuzzy modeling.

Small differences in the input parameters are not or very hard to be discretely converted in a difference in output (risk). In reality, the difference between risky and not risky is not sharp but rather fuzzy. This means that it is not possible to determine exact reference values of risk in this phase of site characterization, and a scientific evaluation of uncertainty must always be considered in the procedure of risk assessment. For this reason, the use of natural language and linguistic values based on fuzzy logic methodology (Munda et al, 1994) might be suitable to make a classification of geological reservoirs based on CO_2 leakage risk. It has for example been used to assess sustainability (Phillis and Andriantiatsaholiniaina, 2000) and in (geological) engineering (Grima, 2000). The features that justify the application of fuzzy are:

- Fuzzy logic has the ability to deal with complex and polymorphous concepts, which are highly submissive to straightforward quantification and contain ambiguities. In addition, reasoning with such ambiguous concepts may not be clear and obvious, but considerably fuzzy.
- Fuzzy logic provides the mathematical tools to cope with ambiguous concepts and reasoning, and finally gives concrete answers to problems full of uncertainty.

The fuzzy logic technique devised by Zadeh (1965) employs human analysis to provide an approximate and yet effective means to describe the behaviour of situations which are too complex or too ill-defined to allow precise mathematical analysis. When the knowledge is intricate and little is known about the relationship between variables, fuzzy expert systems are useful to gather disperse information and to collect certainty about some facts (Veiga and Meech). The principle goal of fuzzy logic rule based modeling is to provide the mechanism to inference[11] with imprecise statements (fuzzy propositions) using the concepts of fuzzy sets and approximated reasoning[12].

In fuzzy logic one first defines linguistic variables which describe approximately the level of performance of the subject. Of a more abstract order are the linguistic terms, which take the (numerical) property values as its input and provide a means to characterize them. They are to be expressed in membership functions, to indicate the contribution of each linguistic term linked via a semantic rule to the degree of membership (Figure 9).

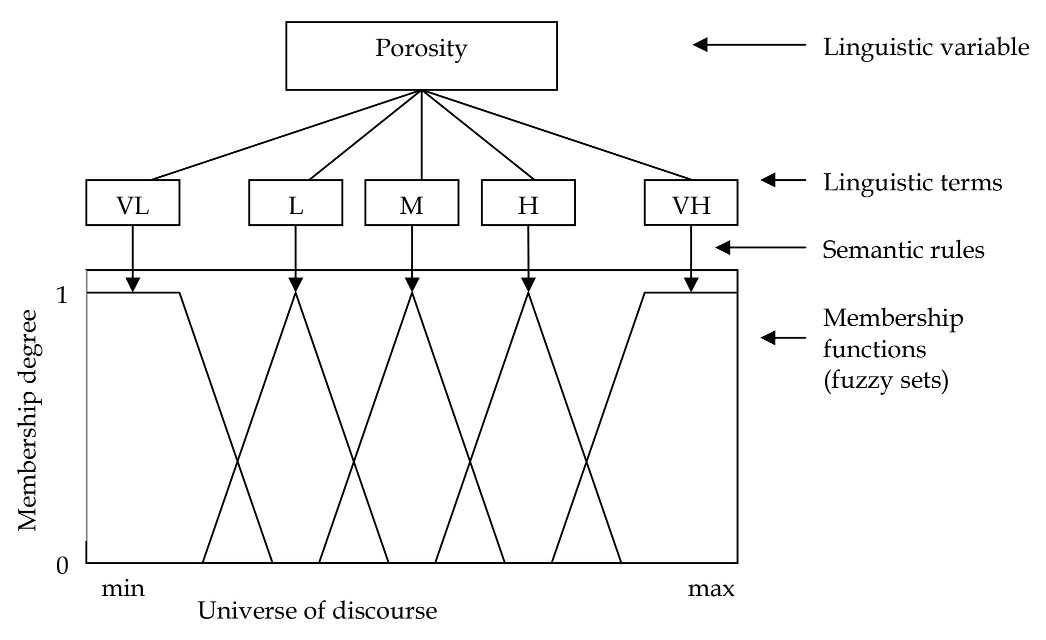


Figure 9 **Example of linguistic variable with triangular membership functions (VL=very low, L=low, M=moderately, H=high, VH=very high) (After Klir&Yuan, 1995)**

To conclude in a rule based fuzzy model, the fuzzy propositions need to be represented by an implication function and are called fuzzy if-then rules (rules of inference). They could take the following general form "If x is A then y is B", where A and B are linguistic variables represented by fuzzy sets on the universe of discourse X.

The fuzzy inference mechanism (modeling algorithm) is the core of a fuzzy model. It is based on a compositional rule of inference (Zadeh, 1973). By using this inference

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[11] the degree of believe one has in a fact or proposition

[12] the mode of reasoning is approximated rather than exact in nature

mechanism an output fuzzy set is obtained given the rules and the input variables (Figure 10). So the consequence (then-part) is based on the coupling of antecedents (if-part). Only rules associated with the linguistic variables that are result of the input, will actually apply to the output.
Defuzzification is the last stage of fuzzy modeling. It implies the translation of a linguistic fuzzy proposition from the output into a crisp numerical value. For this several defuzzification methods have been proposed in literature.

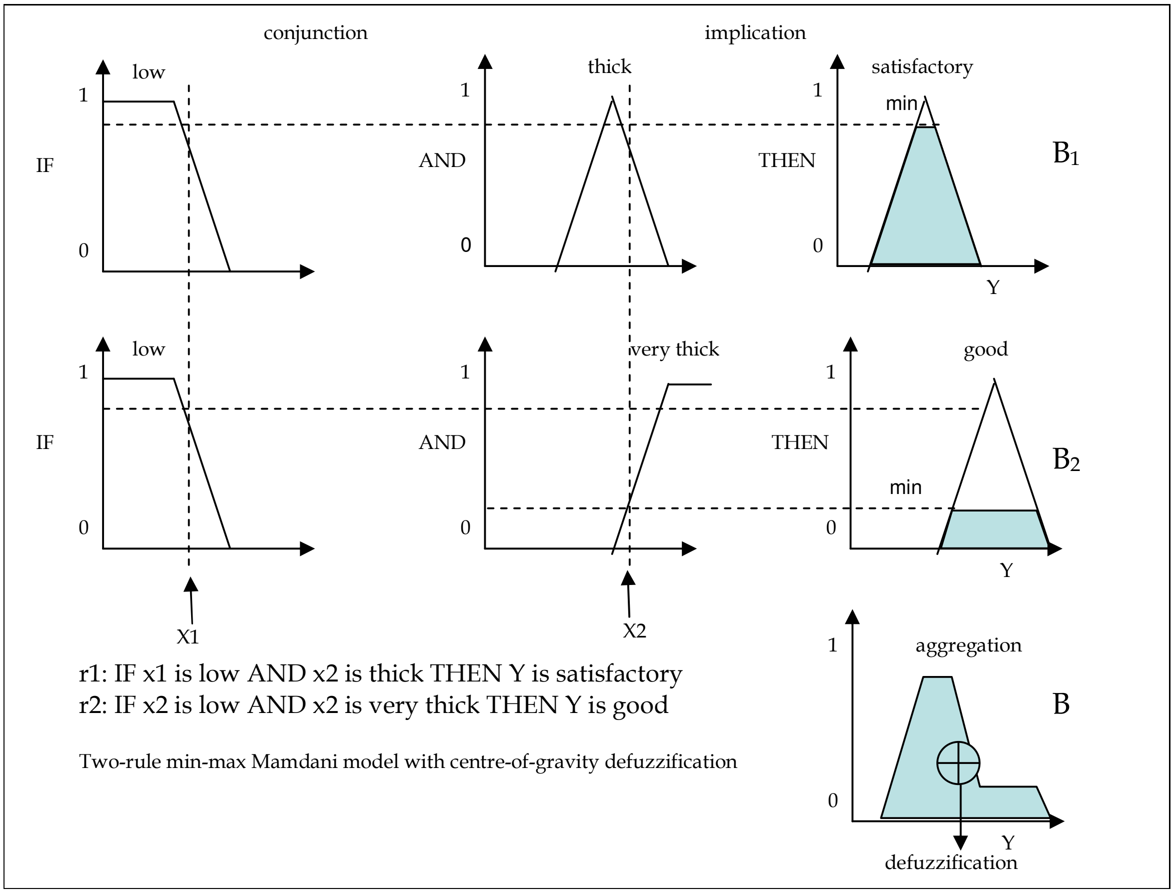

Figure 10 Schematic representation of the fuzzy reasoning mechanism. The fuzzy output is the aggregation of the two clipped fuzzy sets. The outputs are obtained after defuzzification (after Grima, 2000)

In the following chapter it is explained how a fuzzy logic framework can be applied for screening and ranking geological CO_2 storage sites.

4.5 Overview

In the prior sections several methods for assessing risk have been discussed. Table 4 illustrates the six different methods and briefly lists their characteristics. Most of the characteristics are self explanatory, and are as follows:

Goal: the aim of applying the method.
Data needed: refers to what kind of information and knowledge is indispensable to apply the method.

Format: the degree of which the method is ordered and structured.
Major dependencies: refers to which elements in the method are the most sensitive to the outcomes accuracy.
Major applications: in which work area the method has been applied most often.

Table 4 Risk assessment methods

Method	Goal	Data needed	Format	Major dependencies	Major application
DRA	Analytical point estimate calculations	Numerical and qualitative expert knowledge for scenario development and model development	Highly structured	Input parameter	Safety engineering (sensitivity analysis)
PRA	Predict the probability of safety failures of complex systems	Numerical and qualitative expert knowledge for scenario development, model development and quantifying PDF's	Highly Structured	Probabilistic failure information available and model simplifications	Safety engineering
FEP	Scenario development	Qualitative expert knowledge for scenario development	Structured	Expert knowledge and skills	Scenario analysis
MAUT	Evaluation of alternatives in multiple objective situations	Numerical and qualitative expert knowledge for data input, utility measurement and weighting	Structured	Experts risk perception	Decision making
SWIFT	Elaborate hypotheses	Qualitative expert knowledge to identify hazards	Minimal structured	Expert knowledge and skills	Hazard identification in engineering
FL	Cope with uncertainty and variability by formalizing human reasoning	Qualitative and/or quantitative data input, qualitative, intuitive expert knowledge for model development	Structured mathematics, minimal structured linguistic system descriptions	Experts knowledge and risk perception	Control systems

Uncertainty, partially resulting from the risk problem complexity, is another manner to make distinctions between risk assessment methods (see Table 5). Uncertainties on the level of statistics (variations, measurement errors) can be dealt with by means of probabilistic methods. When there is uncertainty on the model level (unreliability), a sensitivity- or scenario analysis could be applied. In case of uncertainty due to vagueness of the problem definition or ambiguity, reasoning on basis of 'what-if scenarios', analogues and fuzzy logic might give solutions. When there is ignorance, risk estimation and control can only be precautionary.

Table 5 **Cope with different kinds of uncertainty (free after Stirling, 2001)**

		Knowledge on results		
		Nature and size	Possible nature	(No) idea
Knowledge on certainty	Accurate	*Statistical uncertainty* Probability distribution (PRA)	Sensitivity analysis (DRA)	*Ambiguity* Fuzzy logic What-If MAUT
	Few	Bayesians	Uncertainty analysis	
	Hardly	*Scenario uncertainty* Scenario analysis (FEP)		*Ignorance* Precaution

5 Application of fuzzy logic to screen and rank geological CO_2 storage sites

This chapter presents the steps and methods used for the construction of the fuzzy model for screening and ranking geological CO_2 storage sites. The fuzzy model contains a knowledge base with the relevant system information and an algorithm to handle with the knowledge base. The knowledge representation is important in making a system understandable and easy to modify. How to deal with uncertainty is crucial in knowledge base systems. In this model this is executed with fuzzy set theory, fuzzy logic and approximated reasoning. The procedure is graphically presented in Figure 11.

The following steps are to be distinguished:

Step 1: Structure selection of the fuzzy model, where the relevant inputs and output are selected by theoretical and expert knowledge and system representation takes place (section 5.1).
Step 2: Design membership functions to represent the knowledge, which is done heuristically. Formulate the fuzzy if-then rules, to be obtained with a MAUT procedure (section 5.2).
Step 3: Apply the fuzzy inference mechanism (min-max Mamdani model) to combine the outcome of the rules and defuzzify to a crisp output (section 5.3).
Step 4: Interpret and verify the model qualitatively (section 5.4).
Step 5: Apply the fuzzy model to perform the evaluation (chapter 6).

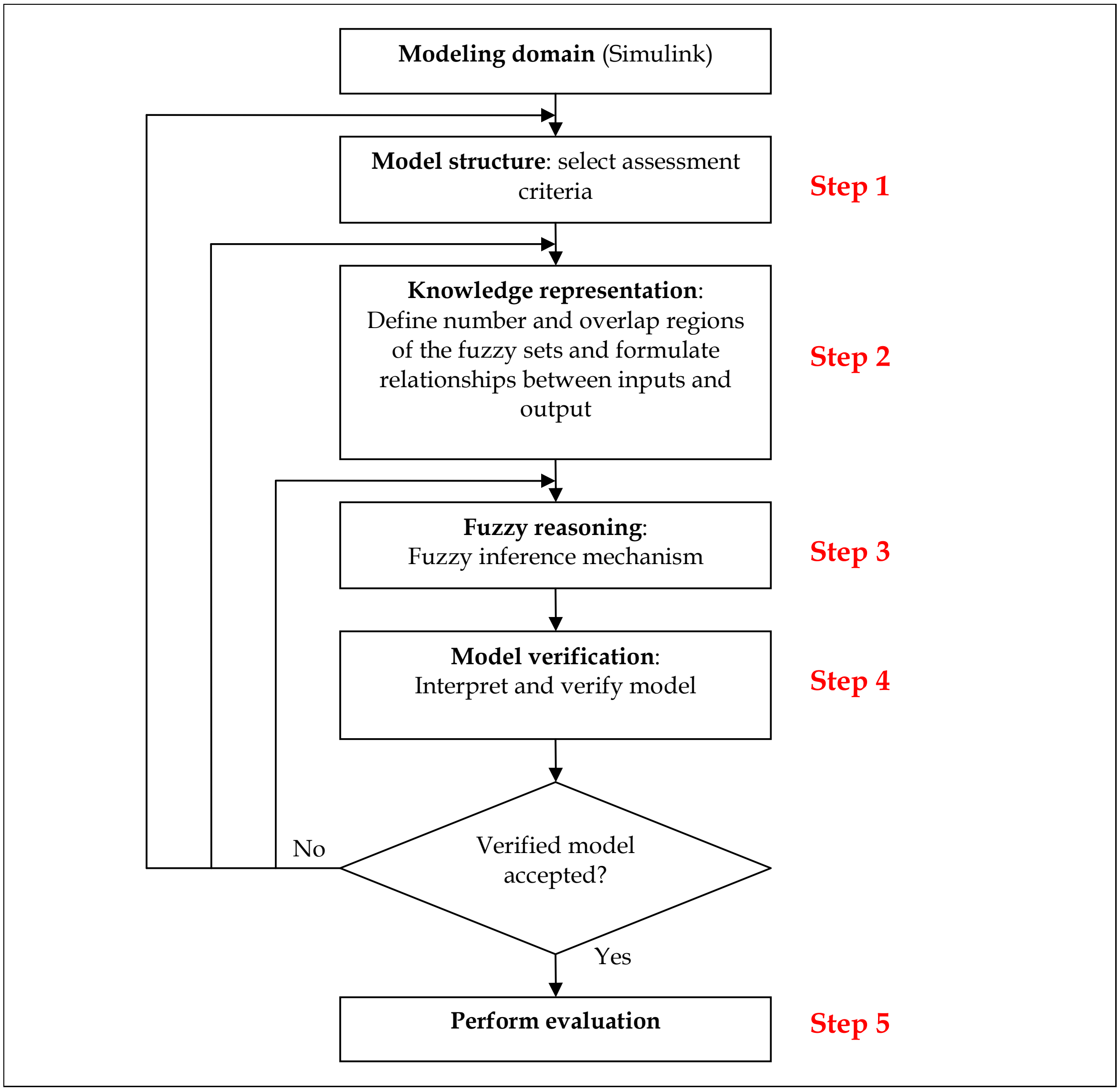

Figure 11 **Construction of the fuzzy logic model**

5.1 Model structure

The structural system decomposition which was done when using a MAUT approach (section 4.3.2), can also be applied in the fuzzy model. With the exception of the properties homogeneity and demonstrated sealing being of a linguistic (fuzzy) type, all other properties are numerically expressed.

Two types of input variables are used in the model, numerical and fuzzy variables. The numerical variables are defined by corresponding membership functions (fuzzy sets) in the universe of discourse (numerical domain) X, $X \subset \Re$ (real numbers). Numerical variables in the model are for instance seal thickness, reservoir depth and numbers of wells per Mt CO_2 storage capacity. The fuzzy variables are defined as set of reference linguistic terms and formally represented as vectors whose domain is the Cartesian product $[0,1]^{N_j}$, where N_j denotes the number of linguistic terms defined for a given variable. However, fuzzy variables do not need to be associated with any numerical domain. Fuzzy variables in the model are for instance seal and reservoir heterogeneity.

5.2 Knowledge representation

5.2.1 Derivation of membership functions

This step aims at capturing the subjective perception of experts in order to model the gradual transition of the terms involved in the description of the system. Here heuristic methods are used for the design, which have been used extensively in rule-based fuzzy modeling (Grima, 2000). The heuristic method employs predefined shapes to represent membership functions.
Designing membership functions is the most difficult, laborious and critical stage of building a fuzzy model, particularly when available knowledge is limited. Membership functions μ_A are always governed by:

$$\mu_A(x): X \rightarrow [0,1] \qquad \textbf{Equation 1}$$

In the model presented here triangular membership functions were chosen for input variables (premises of the rule) and trapezoidal membership functions as output variables, to imply a greater uncertainty. Appendix 3 shows the membership functions used in the fuzzy model for both input and output variables.

It is usually required that the set of linguistic terms satisfies the properties of coverage and semantic soundness (Pedrycz, 1995). Coverage means that each element is assigned to at least one fuzzy set with a nonzero membership degree, i.e.:

$$\forall x, \exists i, \mu_{A_i}(x) > \varepsilon, \qquad \varepsilon \in (0,1) \qquad \textbf{Equation 2}$$

where x is the name of the linguistic variable and A is a set of N linguistic terms of x. We impose a stronger condition, the membership functions satisfy ε-coverage for $\varepsilon = 0.5$.

Semantic soundness is related to the linguistic meaning of the fuzzy sets. The number of linguistic terms and the particular shape and overlap of the membership functions are related to the granularity[13] of the information processing within the fuzzy system, and hence also for the level of precision with which a given system can be represented by a fuzzy model (Babuska, 1995). In consensus with the consulted experts we choose not to divide properties in more than five terms, because system representation and property scale does not allow to do so and to avoid rule-explosion (curse of dimensionality (Jager, 1995)).

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[13] refers to the degree of detail or precision contained in the data.

5.2.2 Formulation of the fuzzy if-then rules

The rule-based formulation is a knowledge representation and each rule consists of two parts, the if-part with multiple premises and the then part with a single consequent. The rules take the following form:

R_i: If x_1 is A_{i1} and x_2 is A_{i2} and…, x_n is A_{in}
Then y is B_i

where x_i (i=1,2,…,n) are the inputs variables (antecedent variables) and y is the output variable (consequent variable). A_{ij} and B_{ij} are linguistic terms (fuzzy sets) that are defined by membership functions A_{ij} (x_j) and B_i, respectively. In the developed fuzzy model the primary concern contain 300 rules, secondary concern contains 180 rules, tertiary concern in total 925 rules divided among the three attributes.
To develop a model which is able to calculate outcomes all rules need to be defined. Since this is a tremendous set it is at the moment impossible to let them all be defined by experts. To have a sufficient set of rules on the short term this will be done with the utility function results (see explanation below), gained from the expert consultancy when applying a MAUT approach.

First, experts were asked to give weight factors to all properties per concern with a swing weighting procedure. Swing weights are numbers between zero and 100 that are associated with each property. Within the weighting procedure, all properties are considered to be at their worst condition. The swing weight of $w^{s,\max} = 100$ is assigned to the property that the expert most strongly preferred to be changed from their worst to their best condition. All of the other properties get a smaller swing weight $w_i^s (i = 1,...,n)$ according to the same procedure. For each property, the direct weight w_i is calculated by division of the swing weight w_i^s by the total sum of all swing weights per concern:

$$w_i = \frac{w_i^s}{\sum_i w^s}$$

Equation 3

One exception has been made with regard to the weighting. Because the tertiary concern is described by many properties it would lead to a very large number of rules (curse of dimensionality) (Ruspini et al, 1998). Therefore here the weighting procedure has been done per attribute rather than for the concern as a whole.

Second, interpolation in the property utility curves results in fixed utility scores u_p corresponding with the linguistic terms. See for example Figure 12. The linguistic term very thin corresponds with a utility score $u_p = 0$, thin with $u_p = 0.5$, intermediate with $u_p = 0.75$, thick with $u_p = 0.9$ and very thick with $u_p = 1$.

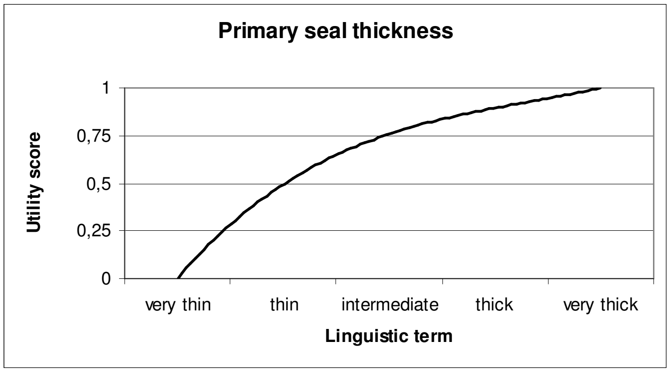

Figure 12 **Primary seal thickness utility curve (represented by trend line)**

An overview of the normalized weight factors and utility curves is shown in Table 6 below. The meaning of the utility functions can be risk aversion (risk avoiding/convex), risk prone (risk taking/concave), risk neutral (no preference/linear) or a combination.

Table 6 **Normalized weight factors and utility curves for rule definition (adapted from Oldenburg, 2005)**

Concern	Attributes	Properties	Weight factor	Utility function
Primary	Wells	well drill date	0.12	risk neutral
		well density	0.38	risk aversion
	Faults	fault density	0.38	risk aversion
		seismic risk	0.12	risk neutral
Secondary	Primary seal	effective porosity	0.24	risk neutral
		thickness	0.24	risk prone
		heterogeneity	0.29	risk neutral
		demonstrated sealing	0.24	risk neutral
Tertiary	Reservoir	effective porosity	0.24	risk neutral
		permeability	0.24	risk neutral
		thickness	0.14	risk neutral
		depth	0.24	risk aversion and risk prone (S)
		heterogeneity	0.14	risk neutral
	Secondary seal	effective porosity	0.26	risk neutral
		depth	0.16	risk aversion and risk prone (S)
		thickness	0.26	risk prone
		heterogeneity	0.32	risk neutral
	Overburden	thickness	0.5	risk prone
		transmissivity	0.5	risk neutral

The third step is to calculate the property score s_i^p and the concern score S_c, which is a summation of the property scores:

$$S_c = \sum_i s^p \text{ where } s_i^p = w_i u_p \qquad \textbf{Equation 4}$$

The last step is to convert the numerical concern score to a linguistic concern term describing the performance of its attributes. This is actually the second step in reverse, now using a concern utility curve. The concern utility curve has a similar meaning as the property utility curve but now it applies to the concern as a whole, with the concern score S_c on the vertical and the linguistic term on the horizontal axis (e.g. very bad, satisfactory, good etc.). Without explicit expert involvement we have defined its shape as an S-curve (Figure 13). This shape implies that there is a risk aversion when the concern scores are low (0-0.35) and risk prone when the concern scores are high (0.65-1). Intermediate scores (0.35-0.65) show risk neutrality, the linear increasing part of the curve.

Figure 13 **Concern performance utility curve (represented by trend line)**

Again, likewise the first step in the formulation of the if-then rules, an exception has been made for the tertiary concern. The curve has been applied per attribute rather than for the concern as a whole.

5.3 Fuzzy reasoning

5.3.1 Fuzzy inference mechanism

Like mentioned before, the fuzzy inference mechanism is based on the compositional rule of inference (Zadeh, 1973). For instance, a fuzzy rule is represented by the Cartesian product (R = X × Y) and is worked out by:

$$\mu_R(x, y) = I(\mu_A(x), \mu_B(y)) \qquad \textbf{Equation 5}$$

where I is the conjunction operator (or t-norm). So for a given input x is A′ and the fuzzy relation R the output (fuzzy set) B′ is obtained by:

$$B' = A' \circ R \qquad \textbf{Equation 6}$$

where the symbol ° means the sup-t composition. Here the minimum for the t-norm is used to compute the membership degree:

$$\mu_B(y) = \sup_x \min(\mu_A(x), \mu_R(x, y)) \qquad \textbf{Equation 7}$$

The minimum t-norm Mamdani implication and the max-min inference method are used here, also referred to as the max-min Mamdani inference method. When this inference method is utilized the min operator is used for the conjunction of the rule and for the implication function and the max operator is used for aggregation of the fuzzy sets. The max-min Mamdani can be summarized as algorithm:

The degree of fulfillment α_i of the antecedent for each rule i is computed:

$$\alpha_i = \mu_{A_{i1}}(x_1) \wedge \mu_{A_{i2}}(x_2) \wedge \ldots \wedge \mu_{A_{in}}(x_n), \qquad \textbf{Equation 8}$$

The output fuzzy set B'_i is derived for each rule using the minimum t-norm:

$$\mu_{B_i'}(y) = \alpha_i \wedge \mu_{B_i}(y), \qquad \textbf{Equation 9}$$

The maximum (union) is used for the aggregated output fuzzy set:

$$\mu_{B'}(y) = \max_{i=1,2\ldots K}\left(\mu_{B_i'}(y)\right) \qquad \textbf{Equation 10}$$

The main reason why this inference method is chosen is that the model contains both fuzzy and crisp inputs. The implication I is selected to be the minimum conjunction operator and the compositional rule of inference (CRI) is simplified to the Mamdani inference method.

The steps proceeding in the model by the fuzzy inference mechanism are:

- At first, the fuzzification translates numerical values of the different attributes into linguistic terms, with their corresponding membership degrees.
- Second, for the degree of fulfillment the membership grades are combined by means of the minimum operator, which represents the premise and connectivity to give the degree of fulfillment of the premise of each score.
- Third, in the inference step the output of each rule is modified using the degree of fulfillment of the premise of that rule. Actually this is the if-then implication of the model and it is implemented by using the Mamdani minimum operator.
- The fourth step is the aggregation, where a combination of the different consequent fuzzy sets into a single fuzzy set by means of the maximum operator.
- Last step is the model output defuzzification.

5.3.2 Defuzzification

The result of the fuzzy inference mechanism B' needs to be translated into a crisp (numerical) output value. The defuzzification is the last step of the fuzzy logic model. The centre of gravity method (cog) is applied here and in a continuous domain defined by:

$$cog(B') = \frac{\int_y \mu_{B'}(y) y dy}{\int_y \mu_{B'}(y) dy}$$ **Equation 11**

where $\mu_{B'}$ is the membership function. It calculates the y coordinate of the centre of gravity of the fuzzy set B′. The COG method is used with the max-min Mamdani inference method, as it provides interpolation between the consequences, in proportion to the height of the individual consequent sets (Jager, 1995).

After defuzzification we have three separate, independent concern scores per assessed site (primary, secondary and tertiary). For the purpose of ranking these scores are to be aggregated into one single score, representing a relative score with regard to leakage risk. This will be done by calculating a weighted average score with normalized weight factors (Table 7). From the table it is clear that for gas fields the importance of well leakage is emphasized and for aquifer traps also cap rock leakage is a main concern (see section 2.2). The weight factors are determined in agreement with an expert.

Table 7 Normalized concern weight factors

	Gas field	**Aquifer trap**
Primary concern	0.6	0.5
Secondary concern	0.3	0.4
Tertiary concern	0.1	0.1

5.4 Model verification

A verification of the rules in terms of consistency and completeness is an important aspect of the validation process. Checking for consistency in a rule base fuzzy model means detecting conflicting rules. A random consistency check with an expert showed no conflicting outcomes, although a complete check is recommended. With the completeness of the rules checking for missing rules is meant. When for certain input values no output values are given the rule base is incomplete. This has been checked with the completeness measure by Jager (1995) and proved to be 1 (strictly complete database):

$$CM(x) = \sum_{k=1}^{Nr} \prod_{i=1}^{Nx} \mu_{A_{i,k}}(x_i)$$ **Equation 12**

where x is an numerical data vector, Nr the number of rules and Nx is the number of fuzzy sets.

6 Results

6.1 Site selection

A selection of possible geological CO_2 storage reservoirs in the onshore Netherlands has been made for screening and ranking. With different geological, spatial and typological characteristics, the discriminative capacity of the method proposed can be examined. In total, fifteen different sites were studied, eight structural aquifer traps and seven (nearly) depleted hydrocarbon fields. In Figure 14 the locations of the sites are given. In Table 8 the geological period distribution is presented. Because sites from Permian and Triassic age preserve the largest storage potential and are expected to be most suitable, more sites are investigated. For each site a fact sheet is prepared with all the relevant assessment information (Appendix 4).

Table 8 Site selection, divided by geological period and type

Era	**Period**	**Gas field**	**Storage potential [MtCO_2]**	**Aquifer trap**	**Storage potential [MtCO_2]**
Cenozoic	Tertiary			NM6	10
Mesozoic	Cretaceous			KN22	6
	Jurassic			S0	4
				AT10	13
	Triassic	Roswinkel	23	RB11	15
		Pernis West	10	RB63	10
		Botlek	20		
Paleozoic	Permian	Slochteren	7512	RO5	32
		Blija Ferwederadeel	17	RO8	17
		Annerveen	213		
		Bergermeer	50		

Figure 14 **Storage locations assessed**

6.2 Results

Figures 15 and 16 depict the results from the fuzzy logic framework. The three independent scores (primary, secondary and tertiary concern) from the model are plotted into one single score. The tertiary concern score is an average of the three attributes scores of tertiary concern (reservoir, secondary seal and overburden). Table 9 presents the ranking results.

Table 9 Ranking results

Ranking #	Aquifer trap	Gas field
1	RO5	Bergermeer
2	NM6	Blija Fewederedeel
3	AT10	Roswinkel
4	RO8	Botlek
5	RB11	Groningen
6	S0	Annerveen
7	RB63	Pernis West
8	KN22	

As for the aquifers (Figure 15), the heavily faulted Rotliegend causes Permian traps to score relatively low primary concern scores even though the well density is low. Their high secondary concern score is caused by the thick, homogeneous Zechstein salt cap rock. Tertiary concern scores are also high due to the good reservoir conditions (Slochteren sandstone; high porosity/permeability/homogeneous), sealing capacities of Zechstein salts and anhydrites acting as secondary seal and the thick overburden.

Triassic aquifer traps show high primary concern scores because of the very low fault density and low well density. Their secondary concern scores are the lowest among the screened sites, caused by high porous, heterogeneous primary seals.

Both Jurassic traps have a quite low fault and well density, resulting in an average primary concern score. Trap AT10 has a fairly good primary seal; it is homogenous, very thick and has a low porosity. Trap S0 instead has a more sandy and high porous primary seal, resulting in a lower secondary concern score. Their poor secondary seal conditions (porous, heterogeneous and shallow location) are causing low tertiary concern scores.

The lower Cretaceous aquifer trap KN22 scores low on all concerns. This is caused by the high fault density, porous and thin primary and secondary seal and shallow reservoir.

For the Tertiary aquifer trap NM6 the absence of wells, a low fault density and homogenous, thick clay acting as primary seal results in high primary and secondary concern scores. The tertiary concern score is average with a medium scoring secondary seal and good reservoir conditions.

As for the gas fields (Figure 16), Permian and Triassic fields have nearly similar primary concern scores. Although Triassic fields have younger wells and a lower seismic risk, the high fault density reduces their score to the same level as Permian fields. The Roswinkel gas field has the highest primary score due to the fact that no major faults are present near the field. For the secondary and tertiary concern scores only the Bergermeer gas field shows real different scores. Because of the thick, low porous Zechstein salt cap rock and the good reservoir and secondary seal conditions it scores slightly better than the other gas fields.

When comparing the results of both typologies we see that aquifer traps show larger differences in all three scores in comparison to the gas field scores. Although the characteristics among gas fields differ from each other they result in similar scores. It appeared that all the selected gas fields have good and bad scoring properties per concern and therefore neutralize each others effect, while some aquifer traps have only good or bad scoring properties and so enhance each other to result in a larger variation in scores.

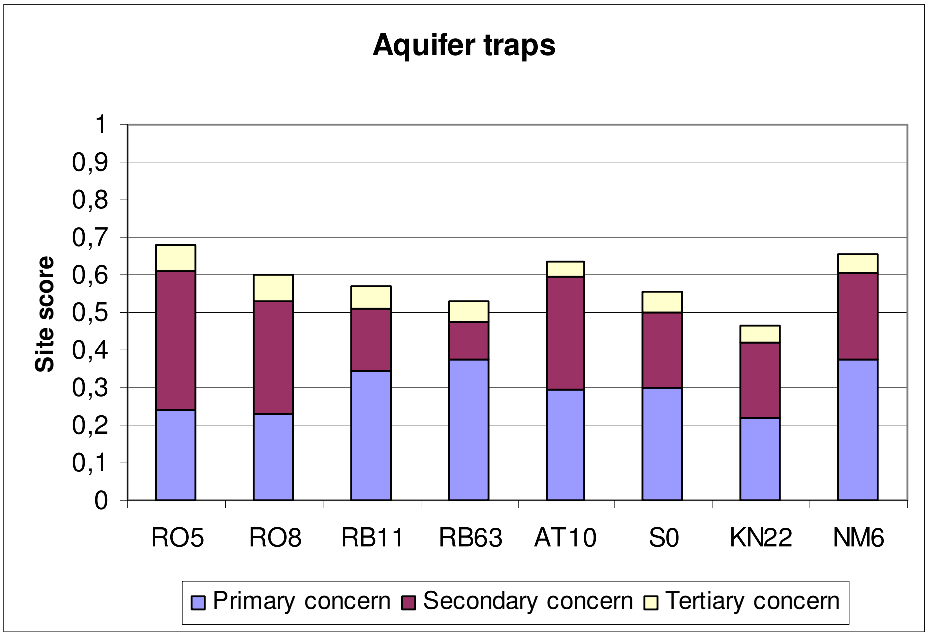

Figure 15 **Aquifer trap scores. The site score represents a relative score with regard to leakage risk and consists of primary concern (well and fault leakage), secondary concern (cap rock) and tertiary concern (secondary seal, reservoir, overburden).**

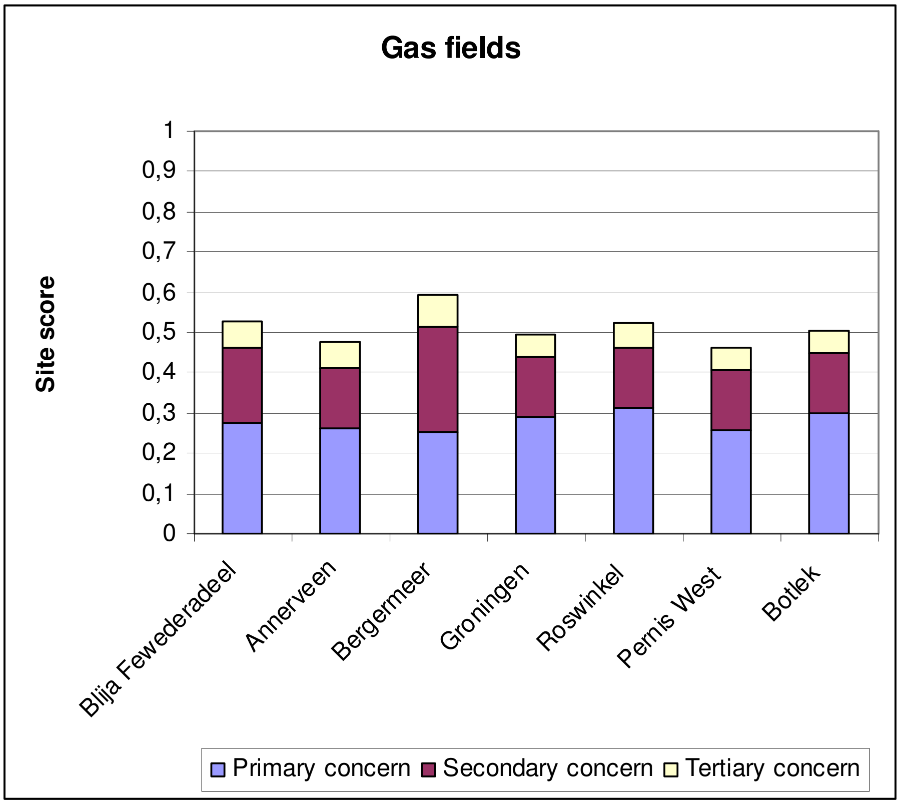

Figure 16 **Gas field scores. The site score represents a relative score with regard to leakage risk and consists of primary concern (well and fault leakage), secondary concern (cap rock) and tertiary concern (secondary seal, reservoir, overburden).**

6.3 Sensitivity analysis

The sensitivity of the fuzzy model to inputs and rules of inference has been evaluated. Only the primary concern has been evaluated. Two different storage sites are chosen as research objects, namely the gas field Bergermeer and the aquifer trap RO8. Because these two sites have different characteristics, the sensitivity for two different settings in the fuzzy model can be examined.

Evaluation of the model sensitivity to inputs has been done by varying one input value and maintaining the others at their reference value, of which the results are showed in Table 10. While varying an input value, the membership degree will differ and possibly an associated linguistic term, but also the if-then rules applied differ[14]. The change is two fold; a physical change of the input and a model setting[15] change at two locations (namely the membership functions and the rules of inference).

Another type of sensitivity evaluated are the rules of inference. By varying the (absolute) weight factors during the MAUT rule defining procedure (section 5.2.2) the outcomes of the rules change. Now there is a model setting change at only one location, the rules of inference. These outcomes are showed in Table 11. In both tables the difference in primary concern score compared to its reference scenario in terms of percentages are given.

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[14] a change of a linguistic term describing an antecedent part of the rule may result in a change of the linguistic term describing the consequent part

[15] membership degree, linguistic terms and rules of inference applied

The results in Table 10 show that the score is increased significantly when properties that are in bad condition in the reference case in comparison to the other properties are strongly (100%) improved. Below a certain threshold, no change occurs. For Bergermeer the fault density and the seismic risk are the worst properties; for RO8 these are the fault density and the well year. The explanation for this non-linear behaviour lies in the membership functions and the utility curve, as will be explained on the basis of the fault density in the RO8 aquifer trap.

A fault density of 1.29 corresponds with the linguistic terms average and high. Because the basis of these triangle membership functions is large, small changes in fault density will not cause other linguistic terms to be descriptive. Therefore the implication of the if-then rule will not change. A large change will however have an effect on the linguistic terms describing the fault density and consequently also the implication of the rule. When the basis of the membership functions is smaller (here: lower fault densities), a small change will likely always have effect on the describing linguistic terms and the rule implication. Because of the chosen membership functions, variations in the well density in this case lead to relatively small changes in primary concern score.

The utility function also has a role, for example the fault density with its risk aversion utility function (convex). Because of the bad conditions (average/high fault density) it has a low utility score (horizontal flat part of the curve). Changing from a high to an average fault density would increase the utility score with 0.15; the implication of the rule will in most cases not change (depended on the other antecedent parts). Changing from a high to a low fault density (steeper part of the curve) would increase the utility score with 0.4; the implication of the rule will probably change. Properties with a linear utility curve cause a more gradual change of the concern score, if they are not dominated by other properties.

Table 10 Sensitivity of primary concern score with varying input values (Ref=reference case property score, []=scale)

	Bergermeer	**RO8**
Primary concern score	**0.419**	**0.458**
Well density	*Ref=0.22 [0-10]*	*Ref=0.12 [0-10]*
+100%	-28%	-10%
+50%	-13%	-5%
-50%	+9%	+4%
-100%	+19%	+9%
Well year	*Ref=1967-1977*	*Ref=<1967*
<1967	0%	-
1967-1977	-	+17%
>1977	+5%	+44%
Fault density	*Ref=0.78 [0-5]*	*Ref=1.29 [0-5]*
+100%	0%	0%
+50%	0%	0%
-50%	0%	+3%
-100%	+45%	+88%
Seismic risk	*Ref=100 [0-100]*	*Ref=0 [0-100]*
0	+45%	-
10	+19%	0%
52	+5%	0%
100	-	0%

Interesting when varying the weight factors is that a decrease in well density weight factor has no effect on the concern score, while a decrease in fault density weight factor is causing an increase of the concern score (see Table 11). This can be explained as follows: in the reference case the fault density is the most dominant property because of its bad conditions and high weight factor. Increasing the weight factor will maintain its dominant position. The implication of the rule will not change. Decreasing its weight factor makes another property more dominant. For both sites this is the well density. The relative contribution of the well density property score increases and so makes it possible to beneficially change the rule implication, resulting in a higher concern score. A similar effect, but now positive, is also possible. The more weight added to the well density, the more dominant it becomes and positively influences the rule implication.
The differences in concern score caused by varying the weight factors of the well year and seismic risk, when comparing Bergermeer and RO8, are due to (nearly-) opposing input values (see reference values Table 10).

Table 11 **Sensitivity of primary concern score with varying weight factors**

	Bergermeer	**RO8**
Primary concern score	**0.419**	**0.458**
Well density	*Ref=10*	*Ref=10*
+100%	+30%	+44%
+50%	+5%	+17%
-50%	0%	0%
Well year	*Ref=3*	*Ref=3*
+100%	+5%	0%
+50%	+5%	0%
-50%	0%	+9%
Fault density	*Ref=10*	*Ref=10*
+100%	0%	0%
+50%	0%	0%
-50%	+5%	+17%
Seismic risk	*Ref=3*	*Ref=3*
+100%	0%	+9%
+50%	0%	+9%
-50%	+5%	0%

The sensitivity analysis demonstrated that the model sensitivity is mainly dependent on the input data and less on the weight factors during the MAUT-procedure. The input data after all determine/affect the degrees of membership and linguistic terms and rules of inference applied. The non-linearity of the hybrid fuzzy logic/MAUT model (in membership functions and utility functions) causes therefore continuous different sensitivities, dependent on the input data.

7 Discussion, conclusions and recommendations

7.1 Discussion

The objective of the thesis was to develop a methodological framework to screen and rank CO_2 reservoirs based on their HSE risk and to demonstrate its applicability to various onshore Dutch storage sites. Therefore the discussion will focus mainly on the developed framework and to a smaller extent on the results from the application.

An actual validation of the fuzzy model did not take place. Although the results are consistent with the general knowledge and expectations, a validation with other screen and rank methods (e.g. Oldenburg, 2005) is suggested. A strong point about the current framework is that a formalization of expert knowledge is to be expressed in a way that it is open to review, critics and revisions. Expert knowledge is the most important input. Consulting the experts in a structured and systematic way, preferably face-to-face, should receive a lot attention. Because of the iterative character of the thesis not all expert consultancies had the initial purpose of contributing directly to the fuzzy model. Some results are transformed in a later stage to serve as valuable input (e.g. utility functions, membership functions), and not all experts that have been part of a first consultancy were part of a second consultancy. This could cause controversy in the information basis. An improvement is possible when more experts are consulted and the knowledge base and experiences with CO_2 storage progresses. A higher expert involvement would also permit the introduction of mutual dependencies.
Qualitative relationships between properties (if-then rules) allow for incorporating mutual dependencies between properties by means of the rule consequent. Because the rule consequences were defined with a MAUT procedure, the mutual dependency still is not present. This can be solved in two ways. The most preferable manner is to let the rules be defined by experts themselves. A formalized way is to introduce a variable weight factor per property, dependent on the values of the other properties.

The use of fuzzy sets allows the generalization of the information used to describe the behaviour of the system and so has the ability to cope with complex non linear systems. Despite its fuzzy character it is transparent and interpretable. Another advantage of fuzzy logic modeling is its incremental or modular character. This flexibility enables new knowledge and insights to be incorporated easily into the model, to improve its performance. Targeted changes could be the adoptions of rules, reshaping membership functions or adding properties. Defining appropriate assessment criteria, collecting data and choosing adequate linguistic terms is indispensable to achieve a better assessment framework. Within the current modeling domain (Simulink) this gives some problems. It requires much manual input (property values), attribute scores have to be calculated separately and it has difficulties in dealing with large amount of rules. Linking Excel or Access based databases with Simulink via Matlab could provide a more automated procedure. A Fortran based model is better equipped to do fuzzy modeling.

The proposed fuzzy logic framework has a wide applicability, but with its current knowledge basis it is limited to Dutch onshore cases. It is developed with knowledge of Dutch onshore sites only, where in case of offshore or other regions outside the Netherlands the model content could remarkably differ. Other types of geology (e.g. different lithology/stratigraphy/tectonic plate characteristics), site characteristics (e.g. well qualities), expert opinions or missing data could lead to model adjustments. A larger set of possible storage sites would be needed to test, apply and validate the method further, perhaps enlarged with offshore sites. The offshore region is not as well mapped as the onshore region and its geology is much less studied, but current research is in progress to do so.

The long duration of CO_2 storage is a particular aspect of this concept, extending possibly for several hundreds to thousands of years after abandonment. Many HSE risks could occur during these timescales, for which hardly any references are available. The main problem is that factual data on safety is missing. This hampers the development of risk assessment frameworks, especially when a limited data set is available and knowledge is limited. Fuzzy logic copes with knowledge uncertainty by using linguistic modeling and approximated reasoning, but the data uncertainty or absence however remains an obstacle. At the moment much effort is put in by geological surveys to gather and document more detailed subsurface data, but geology remains inherently uncertain due to its natural variability. However, a higher data resolution level will not always lead to more accurate results. The many arbitrarily and uncertain elements in the fuzzy logic framework should be kept in mind when evaluating sites and the results must only be seen as a guidance in the selection process. Detailed site-specific research and risk assessments are always essential.

Among some from the MCA community criticism about fuzzy logic remains. The main reasons for this are that there is still a lack of strong arguments that the imprecision that is captured through fuzzy sets and the mathematics carried out actually represent the real fuzziness of perceptions that humans typically display (Chen and Hwang, 1992).

The results allow for some careful generalizations. All gas fields on average score 0.5, and all of them are considered to be suitable storage locations based on a priori expert knowledge. The experiences with UGS in the Netherlands also confirm that (depleted) gas fields are suitable storage locations. With an average score of 0.5 we could set this for now as a threshold to consider a Permian or Triassic gas field to be a suitable storage location. Before extrapolating this also to gas fields from other periods, first a screening of those sites should take place.

Similar kind of generalization can be made for aquifer traps, albeit even more carefully. This is mainly because there is no practical experience in the Dutch region with aquifer storage. With an average score of 0.6 we could set this for now as a threshold to consider an aquifer trap to be a suitable storage location. A clear geological period preference cannot be made yet where more sites from the different periods should be screened first for comparison.

The rather limited discriminative capacity of the model is also a topic of debate. The variation of the final scores is 0.22 for the aquifer traps and 0.13 for the gas fields. An increase in discriminative capacity can be accomplished by narrowing down the property scales and more specified linguistic terms (i.e. replace/resize trapezoidal concern membership function; see Figure 29 in Appendix 2), when there is consensus with experts.
By selecting gas fields with more extreme characteristics (high fault and well density), we could check whether the rather limited discriminative capacity of the current framework can be attributed to the fuzzy model or the data. An increase in discriminative capacity is also possible by narrowing down the property scales and more specified linguistic terms.

7.2 Conclusions and recommendations

In this thesis a methodological framework has been developed to screen and rank potential geological storage sites based on their posed leakage risk. All relevant information needed to perform the evaluation can be subtracted from non-confidential databases and reports. The framework has been applied to several Dutch onshore aquifer traps and (nearly depleted) gas fields. The application showed that an evaluation and ranking of prospective sites with very limited site specific characterization data can be accomplished based on potential CO_2 leakage risk.

The framework for screening and ranking applicant sites for geological CO_2 storage (aquifer traps and gas fields) on the basis of leakage risk is based on storage site decomposition, categorized in three groups of concern. Of primary concern are those attributes that in general influence leakage risk to the greatest extent. These are the wells and faults. Of a lower order is the secondary concern, represented by the primary seal. Tertiary concerns are the reservoir itself, the secondary seal(s) and the overburden which to a lesser extent affect the risk of leakage. Assessing these concerns through evaluation of its attributes which are described by various properties (or assessment criteria, nineteen to describe the system) reveals site concerns and attributes that deserve attention when considering CO_2 storage. The evaluation is done with mainly quantifiable input data and formalized qualitative expert knowledge. A fuzzy logic framework allows the incorporation of imprecise, qualitative knowledge in a systematic way and is able to deal with uncertainties in the knowledge domain by using approximated reasoning. Qualitative relationships between properties are represented by implication (if-then) rules, defined with the use of a MAUT procedure. Expert knowledge was used in assessing utility measurement, property value hierarchy, weight factors and linguistic terms. Defuzzification leads to a crisp score for each group of concern and are to be aggregated into one single score by using weight factors. Two different sets of weight factors are applied to aggregate the concern scores; one for gas fields which emphasized well leakage risk, and one for aquifer traps which emphasized cap rock leakage risk.

Among the aquifer traps the Permian, mid-Jura and Tertiary traps assessed proved to pose the lowest leakage risk. For Permian sites this was mainly due to the good conditions (thick, homogenous and low porous) of the primary seal, whereas for the mid-Jura and Tertiary site this was due to a low fault and well density. All gas fields scored fairly even, only the Bergermeer gas field (Permian age) scored better because of its excellent primary seal conditions. This indicates that Permian sites are very suitable for CO_2 sequestration, but much attention should be given to leakage through faults and abandoned wells. Triassic sites on the other hand are less suitable and may even be avoided because of bad primary seal conditions. If CO_2 sequestration is considered in Triassic sites, leakage through cap rock should receive much observation.

Finally a sensitivity analysis demonstrated that the model sensitivity is very much dependent on the input data and less on the weight factors during the MAUT-procedure. The input data after all initiates the degrees of membership and linguistic terms and rules of inference applied. The non-linearity of the hybrid fuzzy logic/MAUT model (in membership functions and utility functions) causes therefore continuous different sensitivities, dependent on the input data. Varying the weight factors to aggregate the concern scores did not led to complete different results. Those sites that already scored best remain to do so.

It can be concluded that ambiguous concepts with inherent uncertainties and complex behaviour, such as geological CO_2 storage, can often not be dealt with in an easy and transparent way. Especially not when there is a data shortage, the available data has uncertainties and the process described with the data is not understood to its full extent. The involvement of expert knowledge is inevitable in stages where these hiatus exist. Consultancies and questionnaires did showed largely comparative results, indicating a high degree of consensus among experts. The proposed fuzzy logic framework formalizes expert knowledge and contributes to how these complex problems may be dealt with (semi) qualitatively. The results were in agreement with a priori knowledge, but this framework is one of the first attempts to structure and apply that knowledge for purposes of screening and ranking. In spite of some implementation and methodological disadvantages, the results presented suggest that fuzzy set theory, approximated reasoning and rule-based fuzzy modeling helps to construct a workable model. This model can cope with physical insight of the system, subjective uncertainty (e.g. expert knowledge) and imprecise data in a transparent and consistent manner. However, detailed quantitative site research should always be part of a selection procedure and this methodological framework could only be part of a pre-selection procedure.

It is recommended that if possible, the proposed methodological framework should be applied to other potential CO_2 injection sites in the Netherlands to screen, rank and compare their suitability. Modifications, refinements and extensions to improve the framework are possible in several ways. Further suggestions resemble research and developments towards: the use of more detailed data, how to deal or accept the data uncertainty; integration of dealing with both knowledge and data uncertainty in one framework; validation of the model with more expert involvement and another framework; extension of assessment criteria; introduction of mutual dependencies among the properties; other modelling domains; possibilities of combining fuzzy decision tools and probabilistic reasoning when more practical experience is available.

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Appendix 1 Assessment criteria

The first step in a MAUT procedure is to identify and, if necessary, to structure relevant attributes, or here assessment criteria. The attributes should be as much independent as possible. This is performed in an analytical or bottom up way, by reviewing literature and consulting experts.

Primary concern

The primary concern form the most likely and significant leakage processes to occur during the post abandonment phase. These should receive the most attention in all risk assessment studies and studied to the greatest possible extend.

Wells

Wells can potentially provide 'short circuits' for carbon dioxide transport, and therefore need to be included in a leakage risk analysis. When a borehole is drilled to the potential storage reservoir, it creates communication with possible overlying reservoirs and with the surface. Cementing and abandonment procedures are designed to permanently plug such communication channel. At the time of well abandonment, cement plugs tens to hundreds of meter thick are placed at intervals inside the well casing. The intention of borehole sealing is to prevent human access to the sequestered CO_2 and to prevent the borehole from providing a migration pathway for the CO_2. Correct cementing and abandonment operations are essential to achieve restoration of pristine sealing above the designed storage reservoir formation.

Degradation of borehole linings (metal and cement) will occur with time, depending on the natural fluid composition of the deep reservoir and the input of high concentrations of CO_2. Any H_2S present may accelerate corrosion of metal linings. Cement will be attacked by high partial pressures of CO_2, low pH and appreciable concentrations of sulphate, chloride, and magnesium ions in the formation fluids. Seal failure will occur once liners have degraded and corroded (Rochelle et al, 2003). Seal failure may provide preferential short circuits to the surface with potential release of CO_2 and associated contaminants to the surface or near-surface environment. The failure may provide a preferential pathway either through the borehole annulus or around the outside of the casing.

Degradation of the well occurs over time, with cement degradation being the most likely and fastest originating. Therefore, generally the quality of the well is considered to be the most crucial aspect of storage site integrity. The risk of leakage will increase in case of older wells. In 1967 and 1976 the protocol for completing and abandoning wells is improved (aanvullende Mijnbouw regelgeving gerelateerd aan de abandonisering van putten; Staatcourant 100, 1967 / Staatscourant 94, 1976). In the Netherlands the 'Dienst Staatstoezicht op de Mijnen' (survey of state supervision on mines) is the responsible survey for this. From the history of completing and abandoning well instructions it is assumed that wells drilled after 1976 are relatively less sensitive to leakage, while wells drilled before 1967 are relatively more sensitive. Finally, the number of wells (including producing wells) is assumed to indicate the compartmentalization and complexity of the reservoir and presented as the number of wells per storage volume (Mt CO_2).

Faults

The presence of faults is already an indication of potential leakage risk, as mentioned in the thesis. For this purpose a general fault density attribute is included. The dimensionless fault density exists of the parameters fault length, maximum column height and surface and is described by the following relation (van Eijs et al, 2004):

$$\frac{fault\_surface^{3/2}}{gross\_rock\_volume} = \frac{l_b^{3/2} \cdot h^{3/2}}{A \cdot h} = \frac{l_b^{3/2} \cdot \sqrt{h}}{A}$$

Equation 13

where l_b is the total fault length of the intra faults and boundary faults of a reservoir (m), h is the maximum gas column (m) and A the area surface (m^2). Actually, this relation cannot be used in this context because it only holds for gas fields and should contain intra fault lengths as well, where only major fault maps are available for the assessment. Outside the assessment the calculated fault density does not have a meaning, but no better alternative was at hand and so it is included like written above.

It is probable that fault density has a positive correlation with seismic events. Previous studies it already showed that most induced earthquakes originate at locations of weak zones like faults (van Eijs et al, 2004). It is assumed that the higher the fault density is within a region, the bigger the chance on an unwanted seismic event is (Mulders, 2003). Afore mentioned equation is thus used in seismicity studies, but not indicative for seismicity in this attribute.

A seismic event is caused by rapid relative movements within the Earth's crust usually along existing faults. The accompanying release of energy may result in rock movement and/or rupture, e.g. earthquakes. Seismic events may result in changes in the physical properties of rocks due to stress changes and induced hydro geological changes (Holloway, 1996). Injection of CO_2 may cause and trigger seismic events and earthquake hazards through processes such as reducing friction at existing faults. This may occur both in seismically active areas and in areas characterized by low background seismicity (reactivation of ancient fault planes, changes in the orientation, fluid-pockets occurrence). Seismicity can introduce sudden physical changes to the sequestration system and may expose any local population to earthquake hazards. Due to gas exploration many gas fields have already quacked, as a consequence of stress changes. The effects of seismic activity on CO_2 storage reservoirs are still unknown, but reactivating faults is a possible scenario. For this reason a seismicity attribute should be included in the assessment. From an integrated study TNO and KNMI together have conducted an assessment of seismic risks by gas exploration induced earthquakes, by using data from prior earth quakes and subsurface (Wassing et al, 2004). Here, four different classes are divided. Those fields that have quaked before have a chance of 100% to quake again; furthermore there are 52%, 10% and 0% chances distinguished.

On short time scales, the key concerns are issues of connectivity and transmissibility, i.e., can CO_2 flow across a fault into the neighboring compartment. These issues can result in large pressure gradients within an injection reservoir that may change miscibility, injectivity, and in-situ stress. In contrast, long time scale issues such as post-injection leakage concerns are dominated by capillary forces within the sealing rocks. Here, pressure build-up can compromise the integrity of a sealing lithology, inducing either distributed micro-seepage or mechanical failure of the sealing rocks. Such circumstances could result in leakage that is difficult to monitor and mitigate.

Secondary concern

Of secondary concern is the primary seal. This site object is probably only subject of failure when pressure changes in the reservoir take place or leakage caused by primary process. It is much less important due to the dispersed character of the leakage.

Primary seal

The physical and chemical and mineralogical properties of the rocks affect fluid flow and CO_2 migration, determine which water-rock reactions can take place and influence the rock strength and elastic properties (such as compressibility, shear strength, Poisson’s ratio etc). Therefore it is important to include the lithology of the seals, represented by its porosity. Although permeability is an important attribute to describe the primary seal performance, data was not available.

Together with the secondary seal and the overburden this concerns the concept of successive lithological, hydraulic and/or chemical barriers acting successively to prevent fluid escape to surface environments. Features with the potential to retard or prevent CO_2 migration in the geosphere are important considerations when determining the performance of the sequestration site to conserve the stored CO_2. To adequate preserve the CO_2 from migrating, the seal should be homogeneous. Any sandy facieses in the primary seal reduce the spill point depth and thereby decrease reservoir capacity, increase spill point leakage and alter in situ stresses.

A major advantage of former gas and oil fields is their sealing capacities, demonstrated over tens of thousands of years, while in the case of an aquifer there is little evidence that it has substantial sealing capacities. This especially is the case when oil or gas host rock is near the aquifer and nearby exploration takes place, but test wells proved that no hydrocarbons were present. This could indicate that the seal is not proper enough.

Tertiary concern

Of tertiary concern are the reservoir, secondary seal and the overburden characteristics.

Reservoir

Reservoir lithology, the systematic description of rocks in terms of their mineral assemblage and texture, is described by the porosity and permeability. The lithology of the both the reservoir and the cap rock determines the reservoir physical and transport properties (including porosity and permeability). Preferably reservoir rock should have a high porosity, since the proportional increase of storage capacity with an increase of effective porosity, and high permeability to avoid high injection pressures and low injection rates. Potential reservoir lithologies include sandstones and limestones. The lithology of the reservoir rocks affect the capacity to store CO_2, fluid flow and CO_2 migration, determine which water-rock reactions can take place and influence the rock strength and elastic properties (such as compressibility, shear strength, Poisson's ratio etc).

The average thickness of the reservoir is one of the crucial aspects that determine the aerial extend of the CO_2 plume. In reservoirs with a large thickness the CO_2 plume will in general be restricted to a smaller area than in reservoirs with a smaller thickness, or at least extend at a slower speed. This consequently restricts the area of leakage to land surface and the numbers of wells possibly in contact with the reservoir.

The average depth of the reservoir is directly related to the density of the injected CO_2. As shown in the thesis, the density increases with pressure and temperature. At depths lower than 690 meter the CO_2 will be in a gaseous phase and could migrate very easily upwards, since it is lighter than water. But with increasing depth the permeability will reduce, which could create locally very high pressures during injection.

Heterogeneity is the variations in the rock properties of a geological formation and can result in directional variations in permeability, which affects the mobility of fluids and gases in the rock. For example, experience from the Saline Aquifer CO_2 Storage project (SACS) has shown that both stratigraphical and structural local permeability heterogeneities have the potential to profoundly affect CO_2 distribution and migration (Chadwick et al., 2003).

Secondary seal

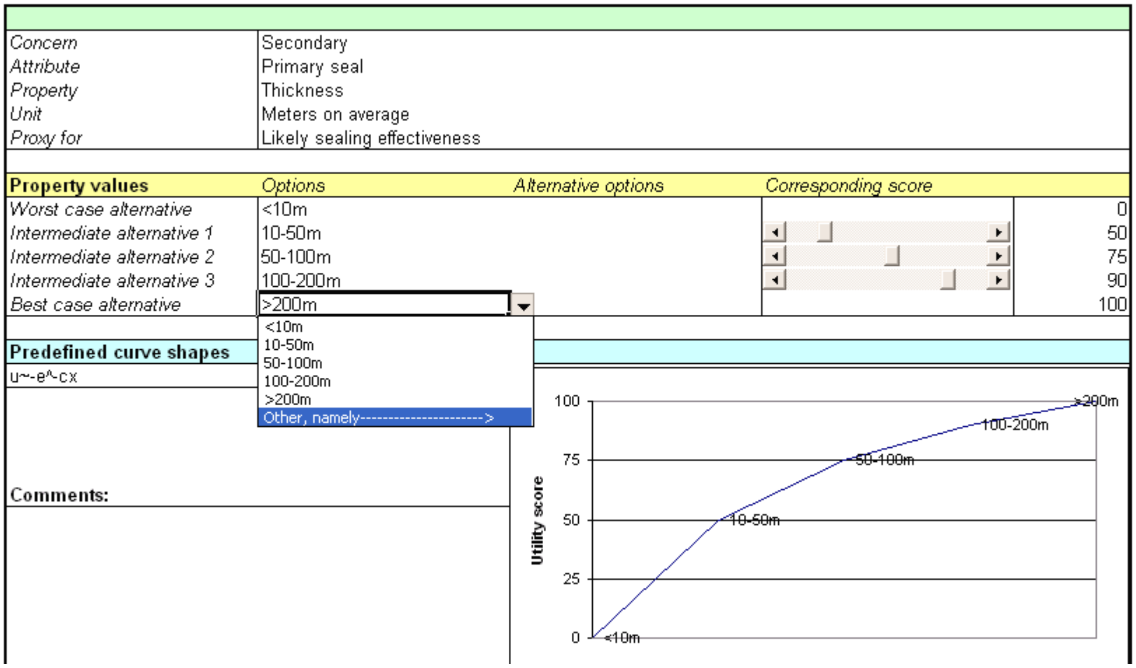
Like the primary seal, the secondary seal also plays a roll in preventing the sequestered CO_2 from migrating to the surface environment, but as a corrective measure. When the primary seal fails for some reason the CO_2 would migrate upwards to a secondary high permeable formation. To analyze the leakage potential of a site it is therefore also worthwhile characterizing the seal of a formation with the ability for secondary containment.

Overburden

Shallow aquifers will be able to dissolve CO_2, reducing further upward migration. The amount of CO_2 that can dissolve will depend on factors such as the location of the water table, the chemical composition of pore waters, CO_2 flux rates, and hydrogeology. The water table location is important in determining the water-body thickness available to interact with any CO_2 rising from depth. The lowering of shallow aquifer piezometric levels reduces the thickness of shallow CO_2-buffering water-bodies. The consequence is a reduced capacity to buffer CO_2 migrating from depth. This attribute is represented by an estimation of total transmissivity in m^2 per day (as Meinardi, 1991 in Defour, 2000). Another general attribute is the total thickness, to denote the dispersive capacities of the overburden.

Aquifers may yield significant amounts of water to wells or surface springs and may thus be a flow path for CO_2 to the surface environment. But shallow well information is limited and dispersed over many regulating and regional governments bodies that it is not included here.

Appendix 2 Expert consultancy



Concern	Secondary
Attribute	Primary seal
Property	Thickness
Unit	Meters on average
Proxy for	Likely sealing effectiveness

Property values	*Options*	*Alternative options*	*Corresponding score*	
Worst case alternative	<10m			0
Intermediate alternative 1	10-50m			50
Intermediate alternative 2	50-100m			75
Intermediate alternative 3	100-200m			90
Best case alternative	>200m			100

Predefined curve shapes

u~-e^-cx

Comments:

Figure 17 **Screenshot of the Excel-based expert consultancy**

The first consultancy of experts had two objectives:

- to acquire a classification of property values and listed according to their preference;
- select a utility curve corresponding to their order of preference.

As can be seen in Figure 17, experts were free to choose different value classes and list them. Secondly they had to choose a utility curve shape. Several were predefined (linear, concave etc.), but a customized curve could also be fitted with the bars on the right.

A second consultancy of experts had the following objectives:

- Give corresponding linguistic terms to the numerical property value classes;
- Define the weight factors.

This second consultancy was only performed with experts from TNO-B&O to get results on a short term. Because of the informal face-to-face consultancy no formal format is used here.

Appendix 3 Membership functions

The membership functions for the primary seal apply also to the secondary seal.

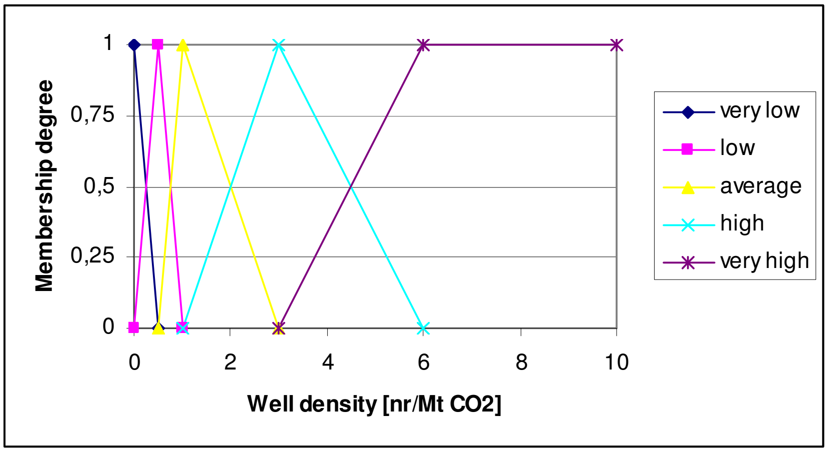


Figure 18 Triangular membership functions for the well density

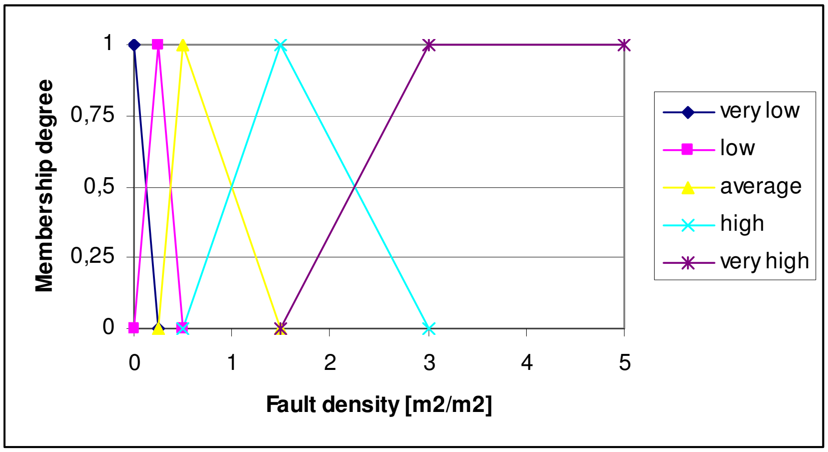


Figure 19 Triangular membership functions for the fault density

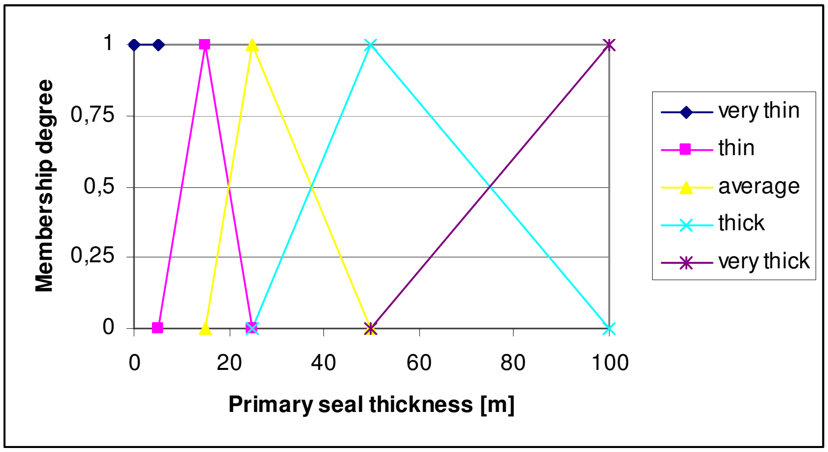


Figure 20 Triangular membership functions for the primary seal thickness

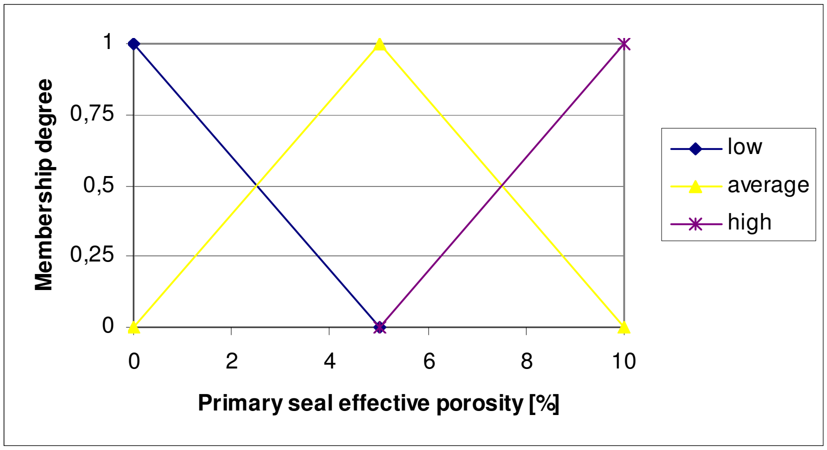


Figure 21 Triangular membership functions for the primary seal effective porosity

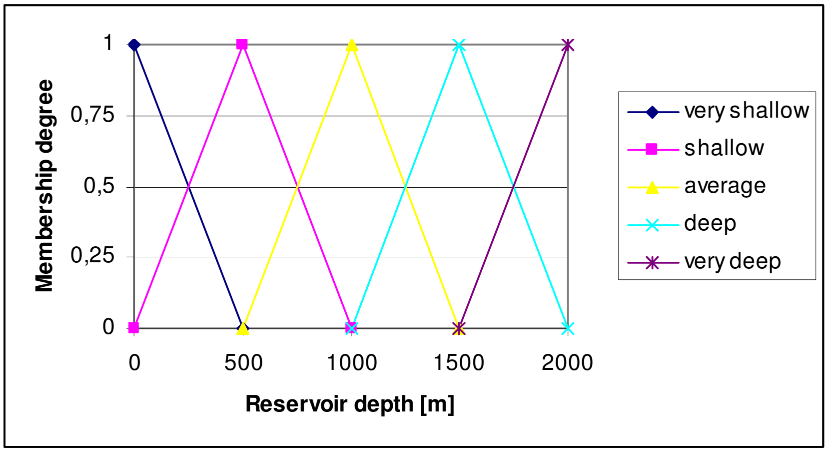


Figure 22 Triangular membership functions for the reservoir depth

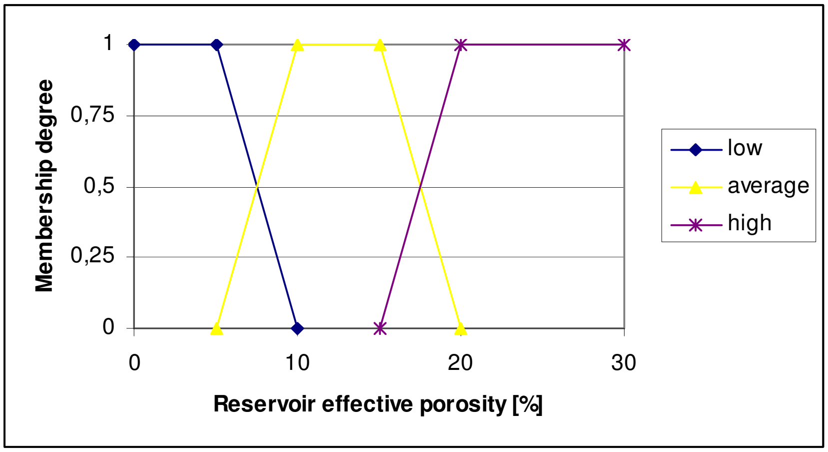


Figure 23 Trapezoidal membership functions for the reservoir effective porosity

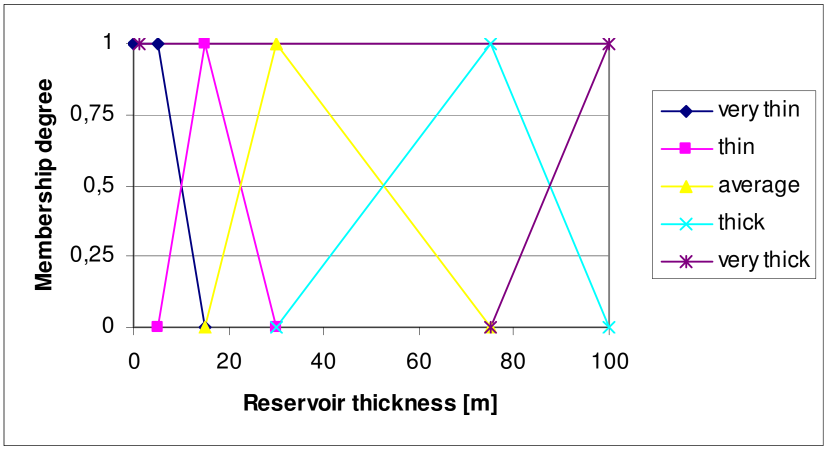


Figure 24 Triangular membership functions for the reservoir thickness

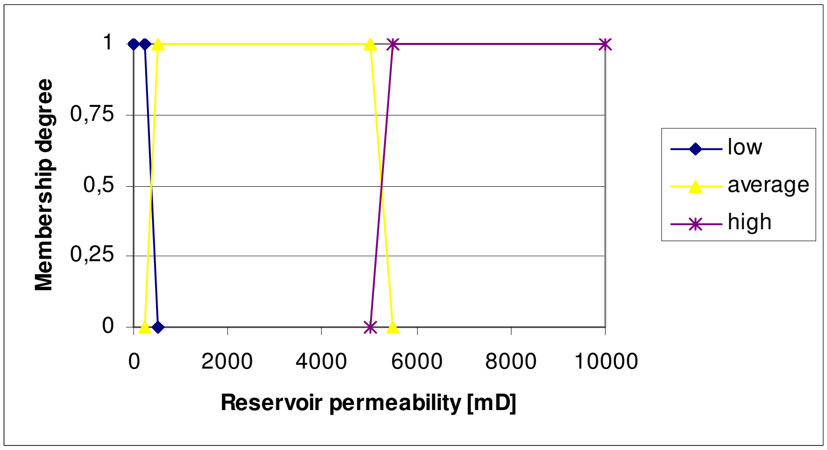


Figure 25 Triangular membership functions for the reservoir permeability

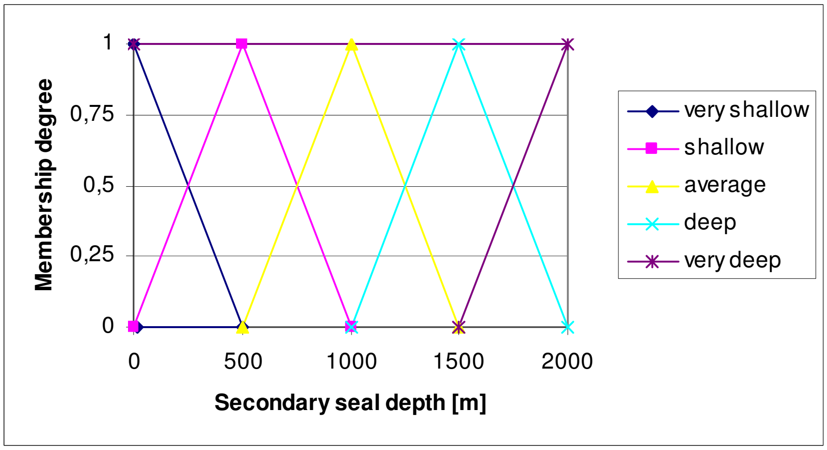


Figure 26 Triangular membership functions for the secondary seal depth

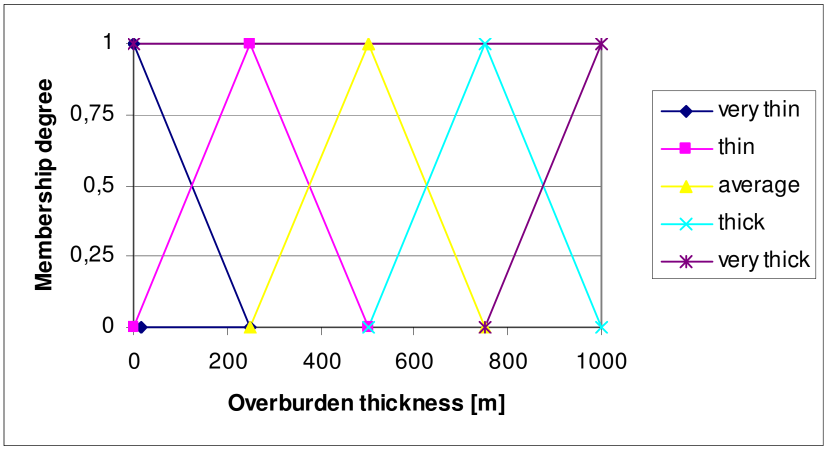


Figure 27 Triangular membership functions for the overburden thickness

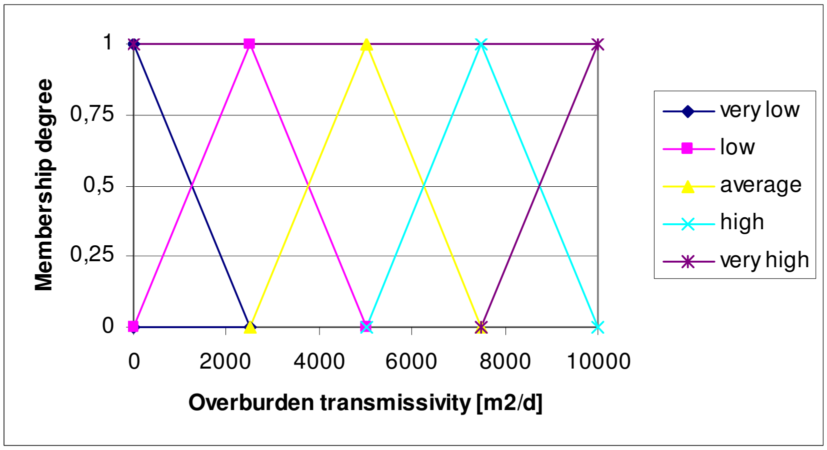


Figure 28 Triangular membership functions for the overburden transmissivity

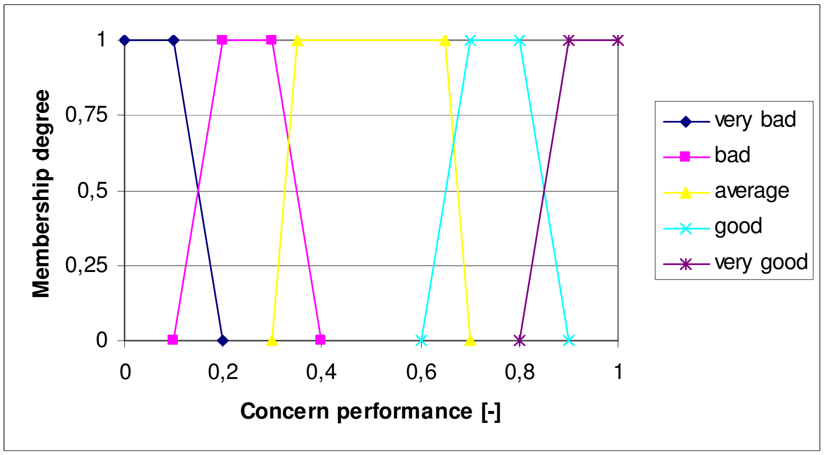


Figure 29 Trapezoidal membership functions for the concern performance

Appendix 4 Fact sheets

FACTSHEET	**RO5**	
General		
Reservoir type		Aquifer trap
Age		Permian
Spatial location	Area number	3
Area size	km^2	37
Estimated capacity	Mt CO_2	32
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.06
Drill year	-	<1967
Faults		
Density	m$_2$/m$_2$	4.06
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	ZEZ1
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	100
Demonstrated sealing	-	Exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	ROSL
Porosity	%	19
Permeability	mD	150
Heterogeneity	-	Low
Depth	m	1974
Thickness	m	182
Secondary seal	Formation	ZEZ2A
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	12
Depth	m	1750
Overburden		
Thickness	m	1788
Transmissivity	m$_2$/d	9,000

FACTSHEET	**RO8**	
General		
Reservoir type		Aquifer trap
Age		Permian
Spatial location	Area number	3
Area size	km^2	34.5
Estimated capacity	Mt CO_2	16.5
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.12
Drill year	-	<1967
Faults		
Density	m_2/m_2	1.29
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	ZEZ1
Porosity	%	0
Heterogeneity	-	Average
Thickness	m	110
Demonstrated sealing	-	No exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	ROSL
Porosity	%	19
Permeability	mD	150
Heterogeneity	-	Low
Depth	m	1748
Thickness	m	199
Secondary seal	Formation	ZEZ2A
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	5
Depth	m	1835
Overburden		
Thickness	m	1638
Transmissivity	m_2/d	10,000

FACTSHEET	**RB11**	
General		
Reservoir type		Aquifer trap
Age		Triassic
Spatial location	Area number	7
Area size	km^2	29
Estimated capacity	Mt CO_2	15
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.07
Drill year	-	1967-1977
Faults		
Density	m_2/m_2	0.41
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	RNSOC/RNROL
Porosity	%	5
Heterogeneity	-	High
Thickness	m	75
Demonstrated sealing	-	No exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	RBMVL/RBMVU/RBMDL/RBMDU/RBMH
Porosity	%	12
Permeability	mD	50
Heterogeneity	-	Average
Depth	m	3045
Thickness	m	203
Secondary seal	Formation	RNROY
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	23
Depth	m	2943
Overburden		
Thickness	m	2970
Transmissivity	m_2/d	5000

FACTSHEET	**RB63**	
General		
Reservoir type		Aquifer trap
Age		Triassic
Spatial location	Area number	6
Area size	km^2	30
Estimated capacity	Mt CO_2	10
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0
Drill year	-	-
Faults		
Density	m_2/m_2	0.43
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	RNSOC/RNROL
Porosity	%	5
Heterogeneity	-	High
Thickness	m	30
Demonstrated sealing	-	No exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	RBMVL/RBMVU/RBMDL/RBMDU/RBMH
Porosity	%	10
Permeability	mD	200
Heterogeneity	-	Average
Depth	m	2200
Thickness	m	174
Secondary seal	Formation	RNROY
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	25
Depth	m	2175
Overburden		
Thickness	m	2170
Transmissivity	m_2/d	900

FACTSHEET	**AT10**	
General		
Reservoir type		Aquifer trap
Age		Middle Jurassic
Spatial location	Area number	5
Area size	km^2	85
Estimated capacity	Mt CO_2	13
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.15
Drill year	-	<1967
Faults		
Density	m_2/m_2	0.38
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	ATWDU
Porosity	%	3
Heterogeneity	-	Low
Thickness	m	200
Demonstrated sealing	-	No exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	ATWDM
Porosity	%	12
Permeability	mD	100
Heterogeneity	-	Average
Depth	m	1275
Thickness	m	66
Secondary seal	Formation	SLDNA
Porosity	%	10
Heterogeneity	-	High
Thickness	m	50
Depth	m	900
Overburden		
Thickness	m	1075
Transmissivity	m_2/d	4000

FACTSHEET	**S0**	
General		
Reservoir type		Aquifer trap
Age		Upper Jurassic
Spatial location	Area number	3
Area size	km^2	17
Estimated capacity	Mt CO_2	4
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0,23
Drill year	-	>1977
Faults		
Density	m_2/m_2	0.55
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	SLDNR
Porosity	%	5
Heterogeneity	-	High
Thickness	m	135
Demonstrated sealing	-	Exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	SLDND+SLDNA
Porosity	%	20
Permeability	mD	500
Heterogeneity	-	High
Depth	m	1360
Thickness	m	195
Secondary seal	Formation	KNNC
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	300
Depth	m	970
Overburden		
Thickness	m	1225
Transmissivity	m_2/d	4000

FACTSHEET	**KN22**	
General		
Reservoir type		Aquifer trap
Age		Lower Cretaceous
Spatial location	Area number	6
Area size	km^2	7
Estimated capacity	Mt CO_2	6
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.16
Drill year	-	<1967
Faults		
Density	m_2/m_2	1,28
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	KNGLL
Porosity	%	10
Heterogeneity	-	Low
Thickness	m	23
Demonstrated sealing	-	Exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	KNNSY+KNNSL
Porosity	%	22
Permeability	mD	100
Heterogeneity	-	Average
Depth	m	780
Thickness	m	172
Secondary seal	Formation	NLLFC
Porosity	%	5
Heterogeneity	-	Average
Thickness	m	20
Depth	m	625
Overburden		
Thickness	m	757
Transmissivity	m_2/d	1000

FACTSHEET	**NM6**	
General		
Reservoir type		Aquifer trap
Age		Tertiary
Spatial location	Area number	7
Area size	km^2	95
Estimated capacity	Mt CO$_2$	10
Primary leakage attributes		
Wells		
Density	nr/Mt CO$_2$	0
Drill year	-	-
Faults		
Density	m$_2$/m$_2$	1.27
Seismic risk	-	0
Secondary leakage attributes		
Primary seal	Formation	NMVFO
Porosity	%	3
Heterogeneity	-	Low
Thickness	m	70
Demonstrated sealing	-	No exploration nearby
Tertiary leakage attributes		
Reservoir	Formation	NMVFV
Porosity	%	17
Permeability	mD	500
Heterogeneity	-	Average
Depth	m	905
Thickness	m	79
Secondary seal	Formation	NU
Porosity	%	10
Heterogeneity	-	Average
Thickness	m	635
Depth	m	0
Overburden		
Thickness	m	835
Transmissivity	m$_2$/d	4500

FACTSHEET	**Groningen**	
General		
Reservoir type		Gasfield
Age		Permian
Spatial location	Area number	1
Area size	km^2	854
Estimated capacity	Mt CO_2	7512
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.05
Drill year	-	<1967
Faults		
Density	m_2/m_2	0.72
Seismic risk	-	1
Secondary leakage attributes		
Primary seal	Formation	ROCLT
Porosity	%	5
Heterogeneity	-	Average
Thickness	m	50
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	ROSLU/ROSLL
Porosity	%	15
Permeability	mD	100
Heterogeneity	-	Average
Depth	m	2820
Thickness	m	134
Secondary seal	Formation	ZEZ1W
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	26
Depth	m	2672
Overburden		
Thickness	m	2870
Transmissivity	m_2/d	200

FACTSHEET	**Annerveen**	
General		
Reservoir type		Gas field
Age		Permian
Spatial location	Area number	1
Area size	km^2	64
Estimated capacity	Mt CO_2	213
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.14
Drill year	-	<1967
Faults		
Density	m_2/m_2	0.97
Seismic risk	-	1
Secondary leakage attributes		
Primary seal	Formation	ROCLT
Porosity	%	5
Heterogeneity	-	Average
Thickness	m	19
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	ROSL
Porosity	%	15
Permeability	mD	100
Heterogeneity	-	Average
Depth	m	3060
Thickness	m	100
Secondary seal	Formation	ZEZ1A
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	26
Depth	m	2920
Overburden		
Thickness	m	2941
Transmissivity	m_2/d	4000

FACTSHEET	**Blija Ferwerderadeel**	
General		
Reservoir type		Gas field
Age		Permian
Spatial location	Area number	2
Area size	km^2	20.9
Estimated capacity	Mt CO_2	17
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.59
Drill year	-	<1967
Faults		
Density	m_2/m_2	0.4
Seismic risk	-	0.098
Secondary leakage attributes		
Primary seal	Formation	ROCLT
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	72
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	ROSLU
Porosity	%	15
Permeability	mD	50
Heterogeneity	-	Low
Depth	m	2570
Thickness	m	105
Secondary seal	Formation	ZEZ1W
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	22
Depth	m	2490
Overburden		
Thickness	m	2548
Transmissivity	m_2/d	5000

FACTSHEET	**Bergermeer**	
General		
Reservoir type		Gas field
Age		Permian
Spatial location	Area number	3
Area size	km^2	7.6
Estimated capacity	Mt CO_2	50
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.22
Drill year	-	1967-1977
Faults		
Density	m^2/m^2	0.78
Seismic risk	-	1
Secondary leakage attributes		
Primary seal	Formation	ZEZ1
Porosity	%	1
Heterogeneity	-	Average
Thickness	m	140
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	ROSL
Porosity	%	22
Permeability	mD	150
Heterogeneity	-	Low
Depth	m	2280
Thickness	m	120
Secondary seal	Formation	ZEZ3A
Porosity	%	0
Heterogeneity	-	Low
Thickness	m	10
Depth	m	1900
Overburden		
Thickness	m	2118
Transmissivity	m^2/d	8000

FACTSHEET	**Botlek**	
General		
Reservoir type		Gas field
Age		Triassic
Spatial location	Area number	6
Area size	km^2	4
Estimated capacity	Mt CO_2	20
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.05
Drill year	-	>1977
Faults		
Density	m_2/m_2	5.5
Seismic risk	-	0.098
Secondary leakage attributes		
Primary seal	Formation	RNSOC/RNROL
Porosity	%	5
Heterogeneity	-	High
Thickness	m	14
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	RBMVL/RBMVU/RBMDL/RBMDU/RBMH
Porosity	%	10
Permeability	mD	200
Heterogeneity	-	Average
Depth	m	2480
Thickness	m	225
Secondary seal	Formation	RNROY
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	22
Depth	m	2432
Overburden		
Thickness	m	2466
Transmissivity	m_2/d	1000

FACTSHEET	**Pernis-West**	
General		
Reservoir type		Gas/Oil field
Age		Triassic
Spatial location	Area number	6
Area size	km^2	3.7
Estimated capacity	Mt CO_2	10
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.7
Drill year	-	>1977
Faults		
Density	m_2/m_2	3.2
Seismic risk	-	0.098
Secondary leakage attributes		
Primary seal	Formation	RNSOC/RNROL
Porosity	%	5
Heterogeneity	-	High
Thickness	m	23
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	RBMVL/RBMVU/RBMDL/RBMDU/RBMH
Porosity	%	10
Permeability	mD	200
Heterogeneity	-	Average
Depth	m	2683
Thickness	m	191
Secondary seal	Formation	RNROY
Porosity	%	3
Heterogeneity	-	Average
Thickness	m	13
Depth	m	2633
Overburden		
Thickness	m	2660
Transmissivity	m_2/d	1000

FACTSHEET	**Roswinkel**	
General		
Reservoir type		Gas field
Age		Triassic
Spatial location	Area number	4
Area size	km^2	21
Estimated capacity	Mt CO_2	23
Primary leakage attributes		
Wells		
Density	nr/Mt CO_2	0.43
Drill year	-	<1967
Faults		
Density	m_2/m_2	0
Seismic risk	-	1
Secondary leakage attributes		
Primary seal	Formation	RBMDC
Porosity	%	5
Heterogeneity	-	Average
Thickness	m	41
Demonstrated sealing	-	Yes
Tertiary leakage attributes		
Reservoir	Formation	RBMVL/RBMDL
Porosity	%	20
Permeability	mD	100
Heterogeneity	-	Average
Depth	m	2100
Thickness	m	45
Secondary seal	Formation	RNSOC
Porosity	%	5
Heterogeneity	-	Average
Thickness	m	90
Depth	m	2070
Overburden		
Thickness	m	2059
Transmissivity	m_2/d	2500