
Environmental Risk Analysis and Management Associated with Carbon Capture and Storage (CCS)

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Declaration of Originality

I declare that this thesis, ‘Environmental Risk Analysis and Management Associated with Carbon Capture and Storage (CCS)’, is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced and with appropriate acknowledgement given.

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Abstract

CCS legislation is currently comprised of an overlapping network of international agreements and regional policies which form a strong basis for environmental protection for potential leakage of CO₂ from underground storage sites. However, these legislative instruments form an uncoordinated legal basis for CCS with overly stringent liability provisions posing a significant barrier to stakeholder investment, technology development and future roll-out of commercial scale CCS projects.

A number of insurance companies have recently developed different types of insurance mechanisms for covering CO₂ storage facilities. Whilst these types of insurance policies are beneficial in encouraging the CCS industry in general, there are also drawbacks. Mostly, they only cover the CO₂ capture facility during the operational phase of power plants or they solely cover the facility for 10 to 30 years after injection has been completed and storage sites have been sealed off.

Furthermore, there is no standard regime for a comprehensive insurance mechanism for commercial scale CO₂ storage facilities due to lack of enough information in regards to the long-term liability of potential CO₂ leakage, type of risks involved in the technology of geological storage of CO₂ and the likelihood of occurrence of these perceived.

This research has identified the main risks associated with CO₂ storage under geological formations and has developed a novel mechanism that enables the insurance industry to assess the risks of CO₂ storage more effectively and therefore adjust their premium rates more in favour of CCS projects. In addition, this will also be beneficial for regulators in enabling them to regulate more effectively in order to incentivise stakeholder participation and investment in the CCS technology. The said mechanism has been developed using a range of systems engineering optimization techniques in order to assess the significance and criticality of the risks of CO₂ leakage through the caprock and their likelihood of occurrence.

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List of Publications

Journal Articles

- Oraee-Mirzamani, B., Cockerill, T., Makuch, Z. (2014). **Quantification of Risks Associated with the Geological Storage of Carbon Dioxide**. In Energy Procedia, Elsevier (In preparation).
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- Makuch, Z., Georgieva, S., & Oraee-Mirzamani, B. (2011). **Carbon Capture and Storage Liability**. In Makuch, Pereira, & Wiley Blackwell Publishing (Eds.), Environmental and Energy Law.

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- Oraee-Mirzamani, B., Cockerill, T., Makuch, Z. (2014). **Quantification of Risks Associated with the Geological Storage of Carbon Dioxide**, 12th International Conference on Greenhouse Gas Technologies (GHGT-12), Austin-USA
- Oraee-Mirzamani B, Cockerill T, Makuch Z (2013), **Environmental risk analysis and risk management techniques associated with CCS: A comparison between the FTA and AHP methods**, UK Carbon Capture and Storage Research Centre (UKCCSRC) Early Career Researcher Annual Meeting: Research and Transitions to Commercialisation
- Oraee-Mirzamani B., Cockerill T., Makuch Z. (2012), **Risk Assessment and Management Associated with CCS**, 11th International Conference on Greenhouse Gas Technologies (GHGT-11), Kyoto-Japan
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- Makuch, Z. , Georgieva, S. Z., Oraee-Mirzamani, B., **Carbon Capture and Storage: Regulating Long Term Liability**, Imperial College London Press, 2011

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- Makuch, Z., Georgieva, S., & Oraee-Mirzamani, B. (2011). **Carbon Capture and Storage in the United Kingdom** (254 pages)

List of Terms and Abbreviations

Acronym	Definition
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
AoS	Appraisal of Sustainability
BP	British Petroleum
CA	Competent Authority
CC&ST	Carbon Capture and Sequestration Technologies Program
CCLR	Carbon and Climate Law Review
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CCSC	Carbon Capture and Storage Community
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
CPR	Commitment Period Reserve
DECC	Department of Energy & Climate Change
DNV	Det Norske Veritas
EC	European Commission
EDZ	Excavation Damaged Zone
EEA	European Environment Agency
EEC	European Economic Community
EEZ	Exclusive Economic Zone
EFAB	Environmental Financial Advisory Board
EGR	Enhanced gas recovery
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ESE	Earth Sciences and Engineering
ETS	Emissions Trading Scheme
EU	European Union
EUA	EU Allowances
FAHP	Fuzzy Analytical Hierarchy Process
FEPA	Food and Environment Protection Act
FS	Financial Security
FTA	Fault Tree Analysis
GD	Guidance Document
GHG	Greenhouse Gases
GHGT	Greenhouse Gas Control Technologies
GISZ	Gas Importation and Storage Zone
IEA	International Energy Agency
IMF	International Monetary Fund
IMO	International Maritime Organization
IPCC	Intergovernmental Panel On Climate Change
LCA	Life Cycle Assessment
LDC	London Dumping Convention
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
NCCCS	The Nottingham Centre for Carbon Capture and Storage
NPS	National Policy Statements

OSPAR	Oslo and Paris Commission
PPC	Pollution Prevention and Control
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
QCCSRC	Qatar Carbonate Capture and Storage Research Centre
RCRA	Resource Conservation and Recovery Act
SCCS	Scottish Carbon Capture and Storage
SDR	Special Drawing Rights
SDWA	Safe Drinking Water Act
TFN	Triangular Fuzzy Number
TOPSIS	Technique for the Order of Preference by Similarity to Ideal Solution
UIC	Underground Injection Control
UKCCSRC	UK Carbon Capture and Storage Research Centre
UNFCCC	United Nations Framework Convention On Climate Change
USDW	Underground Source Drinking Water

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

Human activities every year emit around 25 billion tons of carbon dioxide to the earth's atmosphere and as a result increase the level of greenhouse gas emissions. Furthermore, the concentration of carbon dioxide in the atmosphere has increased dramatically in the 21st century at rate of 2.0 ppm (parts per million) per year from 2000 to 2009 and faster since then (Tans and Keeling, n.d.). According to Tans and Keeling, this increase has been from 280 ppm during pre-industrial times to 395 ppm in 2013 (Earth System Research Laboratory and National Oceanic and Atmospheric Administration) with some researchers believing that this comes from anthropogenic sources (Etheridge et al., 1996).

Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC), global average temperature and sea level are rising, that is attributed to greenhouse gas (GHG) produced by human activities, wherein CO₂ is the largest contributor (Metz et al., 2005). This is said to be creating a dangerous disorder in the climate closer to earth. The forests and oceans absorb around two to three billion (which results in the acidification of the ocean) and seven billion tons of this carbon dioxide every year respectively. Experts estimate that 5 to 10 billion tons of greenhouse gas – more than 40% of the produced carbon dioxide – can be transported out of the atmosphere and be stored in a safe manner.

Moreover, some say that presently the greatest environmental threat facing the globe is climate change (Nilsen, 2008). Climate change is caused by increased levels of greenhouse gases in the atmosphere with carbon dioxide being the significant gas causing global warming. This gas is produced from industries, vehicle emissions and households. According to the IPCC, with the development of the world economy, CO₂ emissions have risen from 280ppm level to 379ppm in the past 100 years (IPCC, 2007). Reduction in the amount of carbon dioxide released from industries would lead to significant cuts in levels of carbon dioxide in the atmosphere thereby helping to control global warming and save the environment from the devastating impacts of global warming.

One option explored in reducing the industrial carbon dioxide emissions is CCS (Gerard and Wilson, 2009). Gerard and Wilson describe CCS as the process where carbon dioxide will be

captured from industrial sources and it is ultimately disposed of by storing it in underground geologic reservoirs rather than releasing it to the atmosphere.

In this chapter, an introduction and some background information is going to be given with regards to Carbon Capture and Storage (CCS), its potential risks from different points of views and the way by which those risks can be potentially quantified in order to decrease their likelihood of occurrence as much as possible.

There has clearly been a tangible progress in the technology to capture carbon dioxide in order to store underground. In addition to the increase in production of renewable energy and promotion of productivity and saving energy, the strategy in which storage of carbon dioxide will have to be carried out can be easily understood by all those who believe fossil fuels should also continue to exist for future generations as for the current one.

Furthermore, this technology provides a unique opportunity to global energy infrastructure in order to overcome the threat that we are facing with regards to global warming. In a world that the amount of carbon dioxide should be heavily restricted, in order for industries such as coal and gas fired power stations, cement and steel plants etc. to be able to continue using fossil fuels as their primary source fuel, countries have to rely on technologies that captures CO₂ from the sources and stores it deep in geological formations.

CCS is believed by many to be a safe and low-cost solution in the reduction of carbon dioxide from the atmosphere on a large scale (International Energy Agency, 2013, Marshall et al., 2007, Energy Technologies Institute, n.d.). However, CCS has to be implemented on a large scale for it to have a chance of reducing CO₂ emissions. In the longer term, assuming the demonstration projects are successful, it is likely that a more integrated approach to CCS development using networks would bring benefits in comparison to multiple isolated facilities (Cockerill et al., 2011). This requires the regulators' and insurance companies' support from regulations and insurance points of views respectively. Insurance companies have to be comfortable and able to insure large scale CCS projects in order to encourage and convince stakeholders about the development and operation of CCS networks. Recent research showed that the extent of any network needs to be carefully considered as more than 50% of the UK's annual electricity derived from CO₂ could currently be collected from a network linking just 8 current power stations, and 60% from a network of 13 power stations (Cockerill et al., 2011).

Newmark and Friedmann et al. argue that CCS is an attractive option as it will allow industries to continue using fossil fuels as it helps to stabilise the atmospheric levels of carbon emissions (Newmark et al., 2010). Moreover, they argue that CCS is both commercially viable and technologically feasible.

Although CCS remains a viable option in helping stabilise the atmospheric carbon dioxide levels, it still has to demonstrate that it is a feasible option in terms of cost and harmlessness to the environment (Utility Week, 2007). This means that it has to be made sure that the risks associated with this technology are well understood and devise strategies to manage and minimise said risks which include risks to the environment and human's health and safety (Farret et al., 2011). The technology of carbon capture and storage is a system with four interrelated elements which should be studied in understanding the risks of the technology. These elements include capture, transport, injection and storage.

1.1. Carbon Dioxide Capture

Carbon dioxide capture is the process in which carbon dioxide is removed from the burning coal, gas or biomass that is used as the fuel for power stations. Although the focus of this technology is mainly on power stations, but some attention is also focussed on steel, cement and other industrial processes.

Carbon dioxide capture is performed using one of three technologies. They are as follows:

- Post-combustion capture: Where the carbon dioxide is captured from the exhausts of coal or gas fired power stations or any other industrial plant after the fuel has been burnt using a specially formulated liquid (Carbon Capture & Storage Association (CCSA), n.d.-c). The captured carbon dioxide is then removed and compressed ready for transport to the storage reservoirs.
- Pre-combustion capture: Where CO₂ is separated from a mixture of hydrogen and CO₂ before the coal or gas has been pre-heated after which the carbon dioxide is ready for transportation to the underground storage reservoirs.
- Oxy-fuel combustion systems: Where the fuel is burned with oxygen instead of air producing a more concentrated carbon dioxide stream which makes the purification

process easier before the compression and transportation to storage reservoirs take place.

1.2. Carbon Dioxide Transport

For the plants that are not directly above underground storage reservoirs, carbon dioxide has to be transported from the point of capture to storage sites. There are two main methods that the captured CO₂ can be transported which are transportation by pipelines and marine transportation i.e. transportation by ships.

According to the IPCC report, pipelines today operate as a mature market technology and are the most common method for transportation of CO₂ and therefore can be used for a means of transportation in a cost effective manner. However, CO₂ can also be liquefied and transported via ships, road or rail tankers that carry CO₂ in insulated tanks at a temperature well below ambient and at much lower pressures (IPCC, 2005).

1.3. Carbon Dioxide Storage

The storage of carbon dioxide takes place either offshore or onshore depending on the countries' available onshore underground storage space. Countries such as the UK for example have many storage reservoirs that can be used offshore in the North Sea.

Carbon dioxide can be stored in different locations. However, the three types of geological formations that have received extensive consideration are depleted oil and gas reservoirs, deep saline formation and unminable coal beds where CO₂ is injected in a dense form into a rock formation below earth's surface (IPCC, 2005).

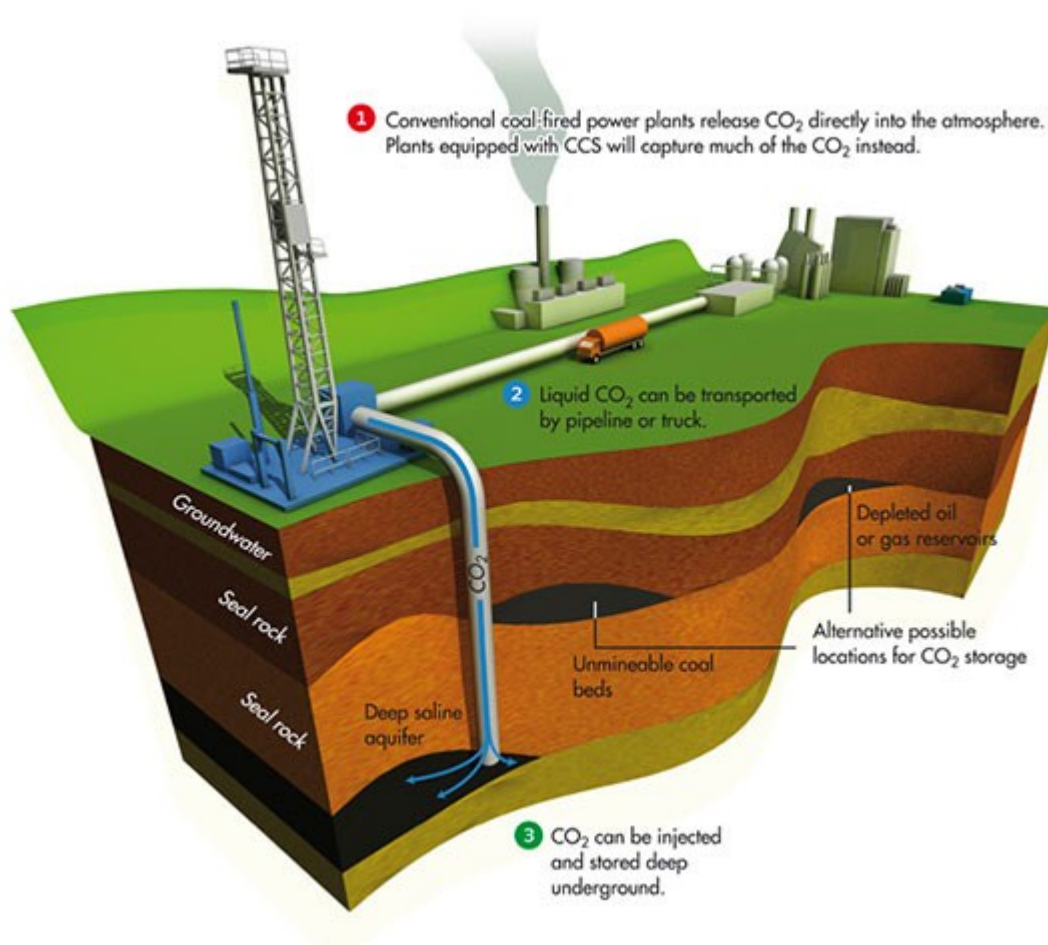


Figure 1, CCS process involves CO₂ capture, CO₂ transport and CO₂ storage (Farret et al., 2011)

Figure 2 shows the ways in which carbon dioxide can be stored under geological formations onshore and offshore with reference to the Enhanced Oil Recovery technology (EOR).

Depending on the nature of the geological formation, the injected CO₂ will then undergo different kinds of changes (in other words, trapping mechanisms) which can potentially include changing from free-phase CO₂ to CO₂ dissolved in water to CO₂ forming minerals over thousands of years. Furthermore, the four trapping mechanisms that ensure the injected CO₂ is held in place are structural (or stratigraphical), residual, solubility and mineral trapping.

In structural trapping, the CO₂ is trapped at the top of an anticline or in a tilted fault block. The sealing rock (caprock) will then prevent the upward movement of CO₂ (Cooperative Research Centre for Greenhouse Gas Technologies (CO₂CRC)). Moreover residual trapping

involves the trapping of CO_2 , in low concentration form, into pore spaces between rocks as a result capillary pressure from the water. Furthermore, as pressure in the reservoir increases, solubility of the injected CO_2 in water increases. Consequently, some CO_2 is dissolves in water and as a result, water becomes denser and begins to sink downwards. This allows for CO_2 to become more dispersed in the water. Over time the amount of dispersed CO_2 in the water can potentially increase (Mitchell et al., 2010). The fourth mechanism by which CO_2 is trapped when injected in to the storage reservoir is mineral trapping. This mechanism occurs when dissolved CO_2 reacts with minerals in the geologic formation creating carbonate minerals which can precipitate (Benson and Cole, 2008).

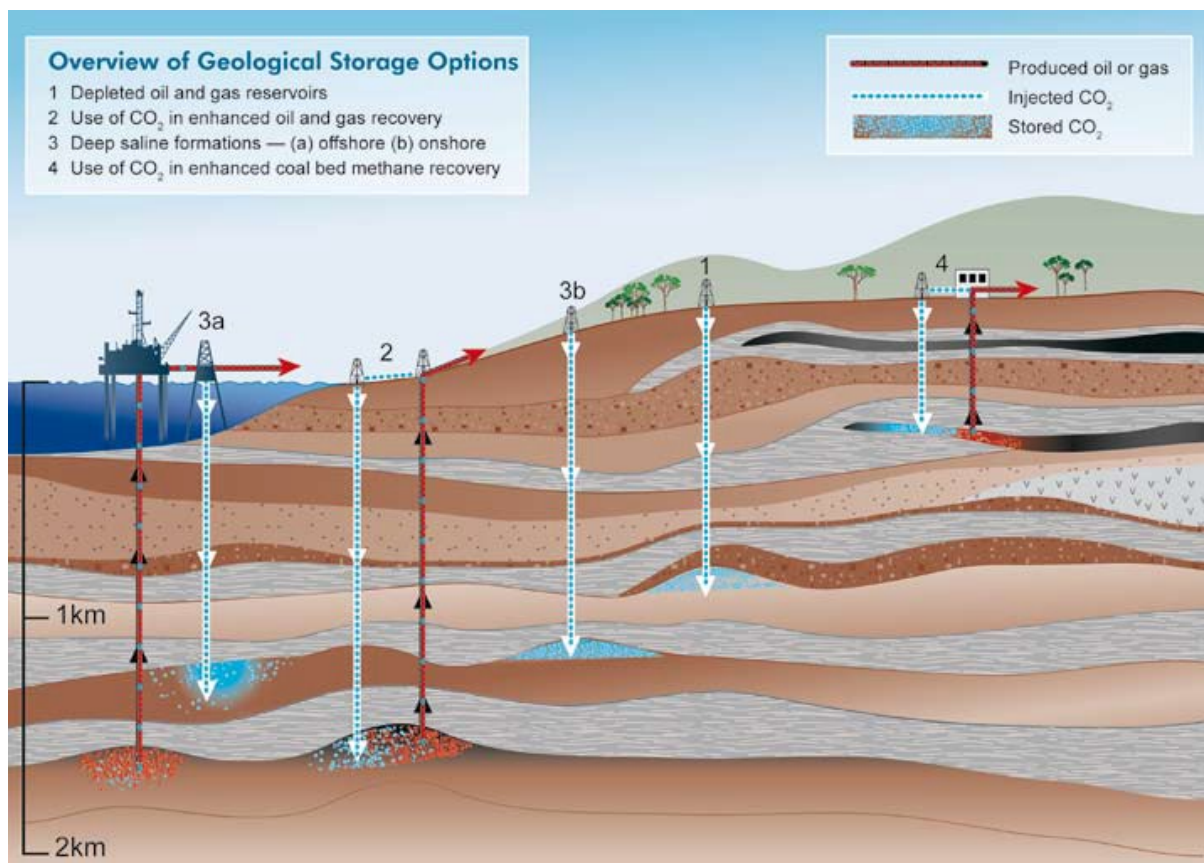


Figure 2, Overview of ways in which CO_2 can be stored under geological formations (IPCC, 2005)

The most important public concern regarding CCS is the risk of leakage back to the surface (land or water). However, no such leaks have been reported in CCS demonstration sites to date. For example, Norway's Sleipner gas field, which is the oldest storage site of CO₂ on an industrial scale, was assessed recently and it was concluded that storage had been successful and that the site was stable and suitable for future storing of CO₂. Moreover, the likelihood of CO₂ leakage in another test site at Weyburn, Canada was determined to be less than one per cent in five thousand years.

Furthermore, in an ideal scenario, a storage site will be positioned away from areas with seismic activity. However, in the case of countries that have been located on tectonically active areas, storage sites may have been located closer to potential earthquake zones. In October 2004, an earthquake occurred close to the Nagaoka CO₂ storage project in Japan. Injection was subsequently stopped immediately and the site was monitored for potential leakages. However, no leakage was detected after monitoring and therefore, injection restarted (British Geological Survey).

As we shall see later on in the thesis, leakage may theoretically occur as a result of injection well failures or leakage up abandoned wells – which could create a sudden and rapid release of CO₂ – and leakage through undetected faults, fractures or through leakage wells – where the release to the surface is more gradual and diffuse (IPCC, 2005).

In the CCS industry, the public, regulatory agencies, customers, governments and in-plant personnel require that companies demonstrate a commitment to control possibilities of incidents and hazards by conducting environmental, health and health related risk assessments. As such, this research project has concentrated only on the storage phase within the CCS chain by studying the ways in which the catastrophic accidents can occur and the ways in which they can be quantified or estimated and then minimised as a result.

There are several methods that can be used in analysing risks involved such as the Fault Tree Analysis technique (FTA), Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA) and Multi-Criteria Decision Making (MCDM) Methods among others. Some of these techniques have been used in other industries such as nuclear, chemical and oil and gas industries but have not been incorporated in analysing the risks associated with CCS even though the risks are similar. FTA and MCDM are examples of these methodologies which

have successfully been used for risk analysis and risk management in nuclear, chemical and waste management industries although they have not been incorporated in the CCS industry.

1.4. Setting the general technical context

In general terms, there are two main possible causes of a leak from a CCS underground storage facility. One is a natural occurrence related to a seismic event and/or tectonic plate shifting. The other is man-made and would probably arise by accident rather than through negligence.

Earthquakes or seismicity is the vibrations or sound waves that are created when rocks slip on a fracture during tectonic plates' constant moving. Natural leaks from a subterranean rock store are more probable after an earthquake or a major landslide. The shock waves created as a result of the seismic events might create exit routes through the rocks, so dislodging the stored gas.

As mentioned before, the captured CO₂ from sources is injected to underground storage reservoirs with high pressure. This high-pressure injection of the gas underground generally does not in itself cause a significant earthquake, but can cause the rocks to slip on a fracture, which therefore causes an earthquake. This is because the injection or withdrawal of a fluid underground has an impact on the pressure balance – where injection or withdrawal of a fluid causes an increase in pressure above the natural pressure, the likelihood of causing a slip (and therefore an earthquake) is greater (Carbon Capture & Storage Association (CCSA), n.d.-b).

Historically, many activities have involved injection and and/or withdrawal of fluids underground such as oil and gas production, geothermal energy production and water injection. These activities all have the potential to cause insignificant earthquakes (less than 4.0 on the Richter scale) as a result of the mechanisms described above that are not normally felt by humans. Moreover, according to research conducted by the Department of Natural Resources and the South Carolina Geological Survey, thousands of earthquakes are recorded every day with magnitudes of less than 3.0 on the Richter scale and 55,000 recorded between 3.0 to 4.9 on the Richter scale every year that can be felt but cause little or no damage (Department of Natural Resources and South Carolina Geological Survey, 2005).

The rock strata containing the captured carbon dioxide using CCS are usually of sedimentary type and are from the era that oil was created. Furthermore, they may have a dip or slope upwards towards the surface and as a result may cause the gas to seep out along the strata to the atmosphere. It may be difficult to follow a rock stratum through the ground to ensure there are no escape routes.

The rocks that will hold the captured CO₂ possibly held oil before, and may crack from any settlement after the oil is withdrawn. This cracking may lead to the leakage of any gas that has been stored there. The pressure on the gas might force it to other areas, where it could escape from the lower rocks into the upper ground and thus into the atmosphere. Gas is a fluid and can travel, unlike nuclear waste which is immobile.

Water erosion of the rock strata might create weaknesses and exit routes for the gas. In limestone and sandstone, weathering during previous glacial periods might create clints (as in limestone pavements) which the gas could use, or where fractures could occur. Furthermore, man-made leaks are possible, for example, after another borehole is put down into the gas holding strata by mistake. Moreover, high pressure carbon dioxide might leak up beside the main injection pipe, pushing out the drilling mud lining the well hole.

In addition, if a drilling hole is not properly filled in and capped after drilling ceases, then it might provide a simple route for high pressure gas to escape. Existing or new coal mines in the same area might also cause settlement of the gas holding strata, and allow an escape of gas through the cracked rocks.

Future search for water or coal might lead to a new well inadvertently being drilled through the CCS strata and cause the stored carbon dioxide to leak.

It is also foreseeable that in some areas in order to use heat pumps in heating houses from hot underground rocks, borehole providing domestic heating might interfere with the CCS storage reservoirs and cause leakage.

For the above reasons, careful planning and technical expertise that exist within the industry sector are more than a match for the technical possibility of leakage established in the above-mentioned anthropogenically-induced scenarios.

1.5. Carbon Capture and Storage in the EU

The European Union (EU) prides itself on taking a leading role in combating climate change and as such is working to reduce greenhouse gas emissions across all of its Member States. Green technology is seen as a lynchpin to its strategy going forward. Among low carbon strategies, CCS is seen as a key contributor and the EU and selected Member States have been broadly reasonable and helpful in taking steps to advance this technology. Accordingly, the European Union wishes to see 20% of greenhouse gas emissions captured using this technology by 2030 with the percentage contribution to rise over a further two decades. However, no low carbon technology is without its challenges. Otherwise, it would already be well-established. In relation to CCS, risk analysis and risk management measures around leakage of carbon dioxide are precisely that challenge.

Thus far, the Directive 2009/31/EC of the European Parliament's (CCS Directive) underlying regulatory approach places a high technical and financial risk burden on industry participation in CCS, featuring uncapped and uncertain long term liability. This is out of step with other regulatory permit-based frameworks (i.e. for oil and gas, nuclear power and waste management industries). Equally, the EU, and, as a consequence of its regulatory framework – a number of her Member States – are not giving the financial assurances to an industry that are already being granted in other competing states (i.e. Canada, Australia, the United States of America and Norway).

As such, the UK, a Member State that is known for its commercial pragmatism, may wish to consider these factors in its CCS Directive transposition strategy. For example, the requirement that storage site operators provide financial security for a worst case scenario with an additional 25% contingency added on top is but one illustration of the challenges that industry may face in implementing the CCS Directive. Another example concerns the apparent requirement that private sector actor's must purchase Emissions Trading Scheme (ETS) allowances if a leak occurs at some point in the future. There is a significant likelihood that allowances will increase in price in the future and though it is unlikely that a leak of the kind that gives rise to liability under the Liability Directive would arise, if it did then the cost of allowance purchases would outstrip any gains from the introduction of CCS in the ETS. What is more, as these allowances are meant to address climate change mitigation and the Directive 2004/35/EC of the European Parliament (Environmental Liability Directive)

already regulates the main environmental impacts associated with climate change, industry is in effect, made to pay potentially twice over for the same leak.

One means of developing greater confidence in the technology is for regulators to cultivate a sense that CCS is not a high risk activity. In turn, this will lead to the development of a nascent CCS insurance market which in turn would solve a range of current stakeholder challenges around risk and liability.

1.6. Timeline of the Development of EU Policy Measures Regarding CCS to Date

Certain EU legislative instruments that have a bearing on CCS began as early as 1996. What follows is a list with the subject matter of the instruments generally being clear as to their application.

- Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances
- Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control (EU ETS Directive).
- Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006, European Union.
- Commission Decision of 30 June 2009 establishing a template for National Renewable Energy Action Plans under Directive 2009/28/EC of the European Parliament and of the Council. Member states have until June 2010 to produce their plans.
- Regulation (EC) No 663/2009 of the European Parliament and of the Council of 13 July 2009 establishing a programme to aid economic recovery by granting Community financial assistance to projects in the field of energy (European

Parliament, 2009b).

- Report from the Commission of 27 April 2010 to the Council and the European Parliament on the implementation of the European Energy Programme for Recovery (European Parliament, 2010b) – Not published in the Official Journal Report offers a state of play on the implementation of the European Energy Programme for Recovery (EPR). Following assessment of the 87 proposals, the Commission decided to grant funding to 58 projects, of which 6 are for the carbon capture and storage (CCS) sector. As soon as the award decisions had been adopted, the Commission started to make the individual legal commitments. In the case of the OWE and CCS, the legal commitments take the form of grant agreements, to be signed by the Commission and the beneficiary. This process is well under way and the Commission considers that all the adopted projects will have legal commitments by the 31 December 2010 deadline set by Regulation (EC) No 663/2009 (European Parliament, 2009a).
- On 10 November 2010, the European Commission has adopted the Communication "Energy 2020 – A strategy for competitive, sustainable and secure energy" (European Parliament, 2010a)
- CONFERENCE – Building Public Awareness of CO₂ Capture and Storage, Draft Programme, 23 Nov 2010
- European Commission's Guidance Document 1 (GD1) on the CO₂ Storage Life Cycle Risk Management Framework addresses the overall framework for geological storage in the CCS Directive for the entire life cycle of geological CO₂ storage activities including its phases, main activities and major regulatory milestones (European Parliament, 2011a)
- This Guidance Document 2 (GD2) builds on the first Guidance Document (GD1) that has laid out the overarching framework and nomenclature for the entire life cycle of geological storage activities including its phases, main activities and major regulatory milestones. This non-legally binding document provides guidance on (European Parliament, 2011b):
 - Site selection;
 - Composition of the CO₂ stream;
 - Monitoring;
 - Corrective measures.

- This Guidance Document 3 (GD3) addresses the issue of transfer of responsibility for all legal obligations from a site operator to the Competent Authority or Authorities (CA or CAs) (European Parliament, 2011c).
- This Guidance Document 4 (GD4) is part of a series of four Guidance Documents each covering different aspects of the geological storage of CO₂. GD4 is to provide guidance on Article 19 financial security and Article 20 financial mechanism (European Parliament, 2011d).

1.7. Aims and objectives of the research

1.7.1. Aims of the research

The aim of this research project is to assess the main risks associated with the storage phase of CCS projects and after doing so, quantify them using different risk analysis methods. In order to do so, risks of carbon dioxide storage have been analysed from a qualitative and quantitative points of views.

With regards to the qualitative risk analysis, the long-term liability of carbon dioxide storage, the regulatory and legislative challenges that storage site operators face have been studied and analysed. In addition, a comparative study was conducted as part of this research in order to compare the regulatory and legislative challenges between different competing states with the UK.

After doing so, a comprehensive literature review was conducted as part of this research project which revealed that extensive research had been carried out in order to evaluate the risks associated with CCS projects qualitatively whereas there had not been a great deal of effort spent on quantifying those risks in order to estimate the probability/likelihood of occurrence, criticality and their subsequent effect on the environment. As a result, this project quantified the risks described in the available literature using five different methodologies. These methodologies each quantified the risks of carbon dioxide storage from different points of views since they each represented a different notion of risk analysis.

The results of this study will consequently be used by the insurance companies in order to calculate and estimate the probability of an undesired event, identify safety critical functions/components/phases and assess the effects of design changes. This will in-turn be

used in order to enable them adjust their present terms and premium rates when insuring CCS projects against its associated risks. Moreover, the findings of this project will help regulators and policy makers better understand and hence legislate more effectively to address the risks associated with CCS projects.

1.7.2. Objectives

The objectives of this research project are predominantly to:

1. Study the regulatory and legislative aspects of carbon dioxide storage, more specifically with regards the long-term liability of storage sites and the potential leakage of carbon dioxide to the atmosphere and the ocean.
2. Study the ways in which other states address the issue of long-term liability
3. Study the risks associated with carbon dioxide storage
4. Conduct consultation amongst experts within academia and the industry
5. Collect data on risks associated with the storage phase of CCS
6. Study the ways by which other industries similar to CCS address those risks
7. Evaluate methodologies in order to quantify the risks discovered
8. Select methodologies that are most suited to perform quantitative risk analysis on carbon dioxide storage
9. Perform quantitative risk analysis in order to estimate likelihood and criticality of the said risks:
 - Conduct a Fault Tree Analysis (FTA) in order to map all the risks involved in this project.
 - Perform risk analysis using the Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP).
10. Draw conclusions with regards to the risks involved in the storage phase of CCS and their probability and likelihood of occurrence along with their criticality in comparison with each other.
11. Use results in order to assist the insurance industry and regulators to gain a better understanding of the risks involved and their significance in terms of likelihood of occurrence and their potential to cause harm to the environment.

Items 1, 2, 3 and 6 have been addressed in chapter 3 of this thesis. Furthermore, item 4 has been addressed in chapter 5 and items 7 and 8 in chapters 2 and 4. Moreover, item 9 has been explained in detail in chapter 6, Appendix I and Appendix II. Finally, items 10 and 11 have been addressed in chapters 7 and 8 of this research thesis.

CHAPTER 2

RISK ANALYSIS

2 RISK ANALYSIS

2.1 Introduction

This chapter falls into nine different sub-sections. The chapter will first begin by looking at the meaning of the word “Risk” and different approaches that exist when it comes to analysing the risks involved in a project (section 2.2). Moreover, this chapter will then present some possible risks that exist within CCS projects and the way in which they compare with the risks in other industries (section 2.3). It will then look at the importance of insurance in the CCS industry and examines the current stage at which the insurance industry is at with regards to insuring CCS projects (section 2.4).

Furthermore, some background information about the analytical methods that were used within this thesis in order to quantify the importance of the risks involved when it comes to storing carbon dioxide deep under geological formations is going to be presented followed by the justification for the use of the said methods.

It should be noted that this research project has solely focussed on the storage aspect within the CCS chain.

2.2 Approaches to Risk Analysis

The word “risk” has varying meanings depending on different contexts. To a common man, risk simply is the concept of probability and severity of an outcome. For example, people do not view death from the impact of an asteroid very risky since the likelihood of such event occurrence is considered to be very small. However, people consider death and injury from criminal related activities as very risky and are widely feared since the occurrence of these events is frequent as reported in the media. Risks involve both adverse results and uncertainty of their occurrence. According to Diakaki et al., risk changes as the related information becomes more specific. In other words, as more information on a certain event becomes clearer, the risk associated with that event may increase or decrease (Diakaki et al., 2006).

The term risk is used in everyday conversation to mean the chance of a disaster. When the term is applied in risk assessment processes, it implies a more specific definition. The widely accepted definition of risk is a combination of chance, or frequency of occurrence of a defined hazard and the magnitude of the consequences of an event (Schwartz et al., 2011). On the other hand, a hazard is described as the potential to cause harm. It is also defined as a situation or property that in specific circumstances could lead to harm.

Risk assessment is used in a variety of professions such as environmental management where it is used to examine environmental problems. Problems such as environmental contamination due to introduction of toxic substances in the environment are complex situations that results in worldwide effects. For a long time, environmental risk assessment methodologies have emphasised examination of the impacts of a problem to the health of humans but more efforts are being made to ensure that risk assessments methodologies assess the ecological effects of any undertaking. Environmental risk assessment evaluates the chances that undesirable effects occur on the environment or the human health as a result of exposure to physical, biological or chemical agents. The evaluation requires an understanding of the undesirable impacts that could result from exposure to chemical agents. In addition, the evaluation requires the knowledge of the duration and intensity required to cause adverse impacts on the environment and the population.

Risk assessment is a necessary tool for organizing, structure and compiling scientific information to enhance the ability of identifying hazardous situations, predict potential problems and set out priorities. It also helps provide a foundation for regulatory control and identification of corrective actions. According to some scientists, the basic principle in risk assessment holds that some risks can be tolerated given that nothing is usually wholly safe. The risk assessment process involves a series of actions starting from hazard identification, exposures assessment, dose-response assessment and risk characterization.

Hazard identification entails identifying the potential adverse effects which a substance has an inherent capacity to cause (European Parliament, 1994). Exposure assessment' is the determination of the emissions, pathways and rates of movement of a substance and its transformation or degradation, in order to estimate the concentrations/doses to which human populations or environmental spheres (water, soil and air) are or may be exposed (European Parliament, 1994).

Furthermore, dose-response assessment involves analysis of the relationship between the level of exposure to a given substance, the frequency and the impact of the effect (White, 2000). Dose-response assessment is described as an estimation of the frequency and severity of an adverse effect which is likely to happen to the human population or part of the environment following actual or envisaged exposure to a substance. In addition, risk characterization is simply defined as the quantification of the probable occurrence of a hazard following exposure to a particular substance (European Parliament, 1994).

As described earlier, CCS is a system having four elements; capture, transport, injection and storage stages. The capture stage involves tapping carbon dioxide produced from industrial facilities to ensure that these emissions are not released into the atmosphere. On the other hand, in the transportation stage, carbon dioxide is condensed or compressed and carried by pipes or ships to the storage site where it will be injected and stored underground. When using a pipe to transport the gas, valves, transitional storage and re-compression stages could be used to operate the pipe or to ensure the safety of the system (Farret et al., 2011). Transportation is followed by injection and Farret explains that the study of the injection stage is important as it joins the injection well to the main tube used to transport the gas (Farret et al., 2011). When drilling a well, there is a particular zone within the rock which appears and is known as the Excavation Damaged Zone (EDZ) which may act as a leakage path in future in addition to the gates used in the transportation pipe (Amann et al., 2009). The storage stage is the last phase of the CCS system and the most important matter that should be considered here is the long-term development of the storage reservoir. This brings the need to understand the type of systems used in CCS projects as this helps predict the behaviour of the system.

Risks arising from systems failure to humans and the environment result from external forces acting on the system, resisting its goals and trying to divert the system from its objective (Ondrey, 2011). Risk analysis of a system involves defining what can go wrong, how likely is it that this event can occur and what the consequences would be should it occur. The biggest risk identified in geological storage of carbon dioxide underground – similar to nuclear and chemical waste management industries – is leakage of material. Leakage can occur as a result of many reasons such as poor quality or aging injection well completion (DiCosmo, 2011). Leakage can also happen in abandoned wells or due to inadequate caprock characterisation.

Moreover, inconsistent and inadequate monitoring can also lead to leakage of CO₂ (Bode and Jung, 2006).

In addition to the potential risks of leakage of carbon dioxide from the geologic reservoirs – therefore making CCS not achieve the envisioned role of atmospheric greenhouse gases stabilization – Gerard and Wilson describe other risks to the environment. Given the volume and the properties of carbon dioxide, the risks associated with CCS will vary depending on the stage at which the project is at and the local and regional geology (Gerard and Wilson, 2009). Rootzén et al., observed that the risks of CCS may reduce with the passage of time (Rootzén et al., 2011). Large surface leakages of carbon dioxide can result in direct risks to the health of humans, both through immediate deaths resulting from asphyxiation or impacts of prolonged exposure to high concentrations of carbon dioxide (Graus et al., 2011). Seepage of carbon dioxide over a long period of time into the subsurface would result in devastating harm to the fauna and flora of the area (Gerard and Wilson, 2009). Consequently, this could disrupt the local ecology and agriculture. This is because living organisms play a critical role in breaking down the organic materials to provide the required nutrients for plant growth. However, these microorganisms require oxygen for respiration as they are aerobic. The other potential risk associated with CCS is that although the gas can stay in the reservoir for a long time, however, it has a potential of displacing saline water into the potable groundwater aquifers (Gerard and Wilson, 2009). Moreover, the injection of carbon dioxide into geological reservoirs can trigger ground heave and seismic events. Gerard and Wilson observe that the probability of the risks described occurring as low. However, they assert that managing CO₂ injection to guarantee human and ecological safety is critical for the success of the program (Gerard and Wilson, 2009).

2.2.1 Quantitative Risk Assessment

Storage of carbon dioxide in deep underground geological reservoirs uses many technologies that have already been developed for use in the nuclear and oil and gas industries. Past experience from oil and gas production, natural gas storage and acid disposal, form a basis from which the risks of geological storage can be evaluated (Benson, 2006). Benson further explains that industrial use of carbon dioxide in various applications offers guidelines for safe handling of carbon dioxide (Benson, 2006). Assessment of the risks of CCS is informed by

wide knowledge developed over the last century on effects of carbon dioxide on humans and the occupational safety in handling CO₂ in industrial settings. In addition, studies on carbon dioxide release in volcanic settings have also enhanced risk assessment in CCS projects (Aksu et al., 2010).

In risk assessment, two quantitative methods are used to estimate the risks of a constructed structure to man and the environment. These are probabilistic and deterministic approaches. In assessing the risks, the first step is to dissect the whole system into the basic elements. The idea behind this approach is that a system's behaviour can be understood clearly from the basic elements that make up the whole system because of lack of adequate data on the behaviour of a system (Kirchsteiger, 1999). As described earlier in this chapter, risks from systems to humans and the environment result from external forces acting on the system and resisting the objectives of the system. In a CCS project, external forces such as a leak can act on the system preventing it from containing the CO₂ in the geological reservoir. This calls for the development of methodologies that can be used to respond to the questions of what can go wrong, how likely is it that an event can occur and in case it occurs, what are the potential consequences (Ingelson et al., 2010).

A CCS system may behave in a deterministic, probabilistic or a chaotic behaviour. These types of systems have been discussed in section 2.2.2.

2.2.2 Deterministic and Probabilistic Systems

Kirchsteiger describes a deterministic system as one which is predictable since they follow a well-known rule. In a deterministic system the components of the system can be described at any time in the future and the past (Kirchsteiger, 1999).

The other type of system is known as a probabilistic system which has some degree of uncertainty in telling how they will behave in future (Glessner and Young, 2008). A CCS system is a probabilistic system since the behaviour of the system cannot be clearly described and this can only be predicted through the use of past knowledge or experience. Furthermore, another type of system is known as a chaotic system which is difficult to predict since they depend on small variations in the current state.

In reality, it is assumed that physical systems flow in a deterministic way. Thereby this method assumes that causes have effects and likewise effects have causes which results in a deterministic flow of events which facilitates perfect prediction of risks without having to use probabilities. The deterministic flow of events is shown in the figure 2 below:

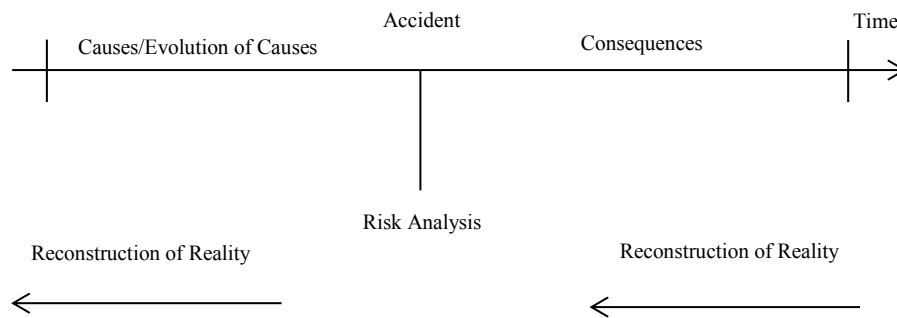


Figure 3, Flow of physical reality versus reconstruction of reality by risk analysis (Kirchsteiger, 1999)

Risk analysis calls for reconstruction of the reality by responding to the three questions described above either by quantitative methods or by qualitative ones. To respond to the question of what can go wrong requires a qualitative analysis which enhances the ability to identify and rank all the possible failure mechanisms which can result in system failure (Nordhaus and Pitlick, 2009).

In the second and third questions, qualitative and quantitative analyses have to be employed. Consequently, deterministic and probabilistic methods can be used in risk assessment in conjunction with each other. Kirchsteiger explains that probabilistic methods are used to reconstruct the reality in cases where incomplete information on the initial conditions of a flow of events is available (Kirchsteiger, 1999).

2.2.3 Advantages and Disadvantages of Deterministic and Probabilistic Methods

Tables 1 and 2 show some of the advantages and disadvantages associated with probabilistic and deterministic risk analysis methods. Unfortunately, there is always some degree of uncertainty when analysing CCS systems and that is the reason why one has to rely on pre-

existing information in order to calculate the probabilities and therefore predict or estimate the likelihood of an undesired events occurrence.

Risk Assessment Method	Advantages	Disadvantages
Deterministic	• The resulting assessment and the process of decision making are usually relatively clear and simple. • Systems analysis and the calculations are well defined. • Answer to decision makers is either safe or not safe (Kirchsteiger, 1999) • Relatively easy to conduct with little effort. • Suitable to be used by engineering personnel who have wide knowledge of the design of plant and operations. However, having experience in performing risk analysis is not necessary.	• It relies on the past experience which in most cases is usually held by a particular person or company (Ondrey, 2011). • Lacks an explicit consideration of the different types of probabilities. • Lacks consistent information on the particular criteria or assessment results. • It is not possible to rank the risks • Since the deterministic method relies on the worst case scenario, there is a danger that systems evaluated using this method are over-stated in terms of the safety levels or protection levels (Ha-Duong and Keith, 2004). • The method is only sufficient for crude identification of internal safety management but cannot be used for risk assessment of events with off-site consequences. This makes the approach not feasible for use in the assessment of risks from CCS project since this can be widespread (Kirchsteiger, 1999).

Table 1, Advantages and disadvantages of a deterministic approach to risk assessment

Risk Assessment Method	Advantages	Disadvantages
Probabilistic	• Integrative and quantitative thereby it allows ordering of results and issues, and explicitly considers and treats all types of uncertainties. • Cost effective to the regulatory authorities since it ensures that resources are directed in dealing with the critical safety issues • The results of the assessment can be communicated clearly and on a well-defined basis. • It can be used when the amount of data is insufficient. • Issue of absolute accuracy is not usually an issue even when the information is limited thereby it helps to make well informed decisions in choosing operation or design alternatives (Kirchsteiger, 1999).	• It is a time consuming and complex method in decision making. Consequently, the assumptions, methods and results used in risk analysis require a person with a background in mathematics.

Table 2, Advantages and disadvantages of a probabilistic approach to risk assessment

2.3 Possible Risks Involved in CCS

Having studied the available literature associated with the CCS technology, table 3 was produced showing some of the possible risks involved in the entire CCS process from technical, financial, environmental, safety issues to regulatory and legislative ones. In some cases, some comparable work that has been carried out in different (yet similar) industries has also been shown such as the Nuclear, Chemical, Oil and Gas and Waste Management (Landfills) industries as well as, EOR and EGR.

Risks	Type of Risk	Comparable Industries
Site selection	Technical	Nuclear new build/high level waste storage and wind farm siting
Injecting operation	Technical	Enhanced oil recovery (EOR), Enhanced gas recovery (EGR), Coal bed methane recovery (CBM)
Closing well	Technical	Oil industry
Stewardship	Technical	Oil industry
Consistency of CO ₂ cap (cap might fracture or become faulty)	Technical	EOR
Economical profit	Financial/Monetary	All industries
Certainty of investment	Financial/Monetary	All industries
Local/regional hazards	Environmental	Oil and Gas, Nuclear, Landfill, EOR, EGR and CBM etc.
Quantitative estimation of CO ₂ emission reduction	Environmental	EOR
Health and Safety issue of area	Safety and Public/Institutional barriers	Oil and Gas, Nuclear, Landfill, EOR, EGR and CBM etc.
System safety	Safety and Public/Institutional barriers	Nuclear, EOR, EGR, CBM, Chemical etc.
Geotechnical safety	Safety and Public/Institutional barriers	EOR, EGR and CBM
Long-term reliability	Safety and Public/Institutional barriers	Nuclear waste and Landfill
Legislation (Environment, Safety and Energy)	Safety and Public/Institutional barriers	Oil and Gas, Nuclear, Landfill, EOR, EGR and CBM etc.
Communication with society	Safety and Public/Institutional barriers	All industries

Table 3, Some of the potential risks that exist within CCS projects

2.4 Insurance in carbon capture and storage projects

Given the risks associated with the CCS technology and the relative advantages of this technology in controlling climate change, it is critical that this technology is implemented on a large scale. However, it is critical to offer insurance as an incentive to companies adopting this technology since in this way they will be able to share the liabilities resulting from any of the risks. Moreover, provision of insurance will give confidence to the public and the society in general in that they would be adequately compensated in an event of potential failures in this technology (Pritchard, 2005). Ruquet observes that insurance companies are realigning themselves to offer insurance for risks on carbon capture and storage in case the technology becomes the primary method of controlling climate change (Ruquet, 2010). Ruquet further states that commercial insurance coverage purchased to cover power, utility and energy clients could be converted into a service to cover CCS clients against the risks (Ruquet, 2010). He however also noted that these discussions are still at an early stage.

One means of developing greater confidence in the CCS technology is for regulators to cultivate a sense that CCS is not a high-risk activity. In turn this will lead to the development of a nascent CCS insurance market, which in turn would solve a range of current stakeholder challenges around risk and liability.

In discussing CCS long-term liabilities, The EU Guidance Document 4 (GD4) demonstrates the knowledge that a risk-sharing approach, such as commercial insurance or risk pooling, would be preferable. However, since they perceive that CCS technology is not well developed and lacks a long empirical history, they posit that a risk-sharing approach would create a high degree of uncertainty in estimating probabilities and magnitudes of potential leakages.

This research project aims to provide the insurance industry with the necessary tools in order to increase their confidence when insuring CCS projects. This will be achieved by providing them with different potential failure mechanisms that can occur in the storage phase (mainly after storage has been completed and storage site has been sealed off) together with the probability and likelihood of the said risks occurring along with the significance of these risks should they occur. This will enable the insurance industry to be able to focus more on the risks that have higher significance and probability of occurrence.

It has to be noted that, some risks might not have high probability of occurrence but might be very significant. In other words, some risks may be very unlikely to cause the carbon dioxide to leak from storage reservoirs and therefore harm humans and the environment but should they do so, then they would have catastrophic consequences with potentially very high leakage rates.

One of the challenges that exist in this case is the uncertainty in the way in which the insurance industry should interpret the results achieved by these types of quantitative risk analyses in order to adjust their premium rates accordingly. This is something that has to be addressed in future research and indeed is going to be addressed to some extent within this thesis.

With regards to the CO₂ storage facility insurance, it has to be noted that, there are currently insurance companies that cover risks associated with operational and decommissioning activities but not the post-closure risks. However, this might change should a regularity cap is introduced to be put on the risks. More information with regards the current insurance market has been given in section 4.2.1 of chapter 4.

2.5 Modes of decision-making

When one is required to make a decision, one is faced with either a continuous or discrete space. Furthermore, decisions that have to be made may be dependent on a single criterion or it can well be dependent on multiple criteria. These criteria can be quantitative, qualitative or a combination of both. Of course, the method of decision making needed to be used in each will have to be different.

In discrete spaces with a single criterion, decision making is simple and convenient. An example of this is when one is required to choose the shortest route out of n number of routes. This selection is done very easily since it is a quantitative one. However, when the selection needs to be a qualitative one, then it is a much harder task to choose between one another. In this case, firstly, the term “shortest distance” has to be defined and then the available options have to be ranked according to their distance. In case of having multiple criteria, in addition

to the above problem, the conversion of the criteria also adds to the challenges that one has to overcome.

According to Haimes et al., the term *risk assessment* means identifying “risk scenarios”, i.e., determining what can go wrong in the system and all the associated consequences and likelihoods (Haimes et al., 2002). They further explain that the steps after determination of what can go wrong are to generate mitigation options, evaluate each in terms of its cost, benefit and risk trade-offs and then decide which options to implement and in what order (Haimes et al., 2002). Therefore, ranking the risks associated in any project in accordance with their criticality and importance can help in deciding which risk scenarios contribute most towards the main risks so that more attention can be focused on them.

The need for ranking the risks arises in a variety of situations. The following are a few examples where risk ranking is not only desirable but essential: thousands of military and civilian sites have been contaminated with toxic substances; myriad sources of risk are commonly identified during the development of software-intensive engineering systems; and each year thousands of the space shuttle’s mechanical and electronic components are placed on Critical Item List (CIL) to identify items that contribute significantly to program risk.

The common element in such risk identification procedures is the need to establish prioritise among a large number of individual contributions to the overall system risk. A dependable and efficient ranking of identified risk elements can be a step toward systemic risk reduction. The Analytical Hierarchy Process (AHP) method was invented to attempt to solve such problems.

2.6 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a mathematical method that derives ratio scales from paired comparisons. AHP was first introduced by Professor Thomas. LC. Saaty in 1970s, however, its extensive review in academic and professional circles was done in mid-1980s. Numerous articles have been written and many expert analyses have been carried out with regards to the effective and broad spectrum of this method. AHP is used in many fields such as strategic marketing, resource allocation, technology selection, risk

analysis/assessment, marketing strategies, asset allocation and evaluating of engineering projects, production and operations management, assessment of personnel as well as economic, political and sociological issues. The advantages of this theory are many and the concept is very easy. Furthermore, this method can be easily applied in order to solve complex problems whether they are multi-objective, multi-variable or multi-time problems. Moreover, AHP can lead one to a detailed understanding of the goal of the problem and stabilise judgments.

Multiple Attribute Decision Making (MADM) methods which deal with the problem of choosing an alternative from a set of alternatives are characterised in terms of their attributes. Usually, within MADMs a single goal exists which can be of two different types. The first type is where the goal is to select an alternative from a set of scored alternatives based on the values of their importance/significance. The second type of goal is to classify alternatives, using a kind of role model or similar cases. MADM is a qualitative approach due to the existence of criteria subjectivity (Saaty, 1978a). When using this method, the decision maker has to define a ranking mechanism for the criteria as importance or weights. There are many forms for expressing these weights, but the most common are: Utility Performance Function, Analytical Hierarchy Process (Saaty, 1978b, Yager, 1978), and Fuzzy Version of the classical linear weighted average (Baas and Kwakernaak, 1977, Baldwin and Guilg, 1979). AHP is a multi-criteria decision method that uses hierarchical structures to solve complicated, unstructured decision problems, especially in situations where there are important qualitative aspects that must be considered in conjunction with various measurable quantitative factors.

The AHP method is useful and effective way to prioritise between a set of alternatives taking into account certain criteria which will have to be defined. Furthermore, because of the sophisticated nature but yet ease of use and applicability to a wide range of decision-making problems, AHP has been popular amongst scientists from different fields.

Yu et al. applied the AHP method in order to select a suitable site for the geological storage of carbon dioxide in Taiwan taking into account different criteria such as economics, safety requirements, storage effectiveness and storage capacity (Yu et al., 2011). Furthermore, Promentilla et al. have used AHP along with its more generalised approach, Analytical Network Process (ANP), and have as a result analysed and therefore proposed potential CO₂ sources and sinks in a CCS system (Promentilla et al., 2013). In addition, Tan and

Promentilla proposed a modified form of AHP for ranking storage sites upon introduction of new information (Tan and Promentilla, 2013).

The AHP technique has also been used extensively in other research areas in the field of energy. Kagazyo et al. used AHP in order to evaluate and prioritise energy-related projects taking into account technological issues as well as resources and social aspects (Kagazyo et al., 1997). They further subdivided each category forming a tree-like hierarchy with nineteen energy-related characteristics and seven environmental characteristics in order to evaluate research projects and as a result have identified short, intermediate and long-range strategies for Japan, short and intermediate range strategies for less developed countries and intermediate and long-range strategies for all other countries (Kagazyo et al., 1997).

Others have used different applications of the AHP in order to perform analyses such as to assess domestic solar heating systems (Mohsen and Akash, 1997, Chedid, 2002), evaluate and allocate energy resources (Ramanathan and Ganesh, 1995a, Ramanathan and Ganesh, 1995b), prioritise public transportation plans (Poh and Ang, 1999, Tzeng et al., 2005) and environmental cost analysis (Huang et al., 1997, Huang et al., 1996).

Moreover, in another study, Lee and colleagues analysed the potential competitiveness of Korea's ability in the development of hydrogen energy technology using the AHP technique. Furthermore, Aragonés-Beltrán et al. used an AHP/ANP approach in order to assist a Spanish solar power investment company to decide whether or not to invest in a particular solar-thermal power plant project and if so, to prioritise the projects in the company's portfolio (Aragonés-Beltrán et al., 2014).

The AHP method – described in detail in sections 2.6 and 3.4 of chapters 2 and 3 respectively – has been used in this study in order to evaluate the importance of each risk element within the fault tree that was developed – shown in figure 7 in section 4.3 – in comparison with other risk elements. However, since the AHP method is not a scientific method and can be inaccurate at times, it was decided to use the TOPSIS and PROMETHEE methods in order to test the robustness and validate the AHP method and to inspect whether or not they produce different results to the AHP method. The said two methods have been described in chapter 7 and the calculation steps have been described in section 10.1.1 of Appendix I.

The AHP method has been used in order to calculate importance weights for each risk element within the fault tree developed in this project – using the output of the ‘expert consultation’ stage of this study – and therefore, assess the likelihood of the said risks.

The AHP is based on four main axioms (Saaty, 1980):

1. Given any two alternatives (or sub-criterion), the decision-maker is able to provide a pairwise comparison of these alternatives under any criterion on a ratio scale which is reciprocal.
2. When comparing two alternatives, the decision-maker never judges one to be infinitely better than another under any criterion.
3. One can formulate the decision problem as a hierarchy.
4. All criteria and alternatives which impact a decision-problem are represented in the hierarchy.

2.6.1 Advantages and Disadvantages of Analytic Hierarchy Process (AHP)

Table 4 shows the general advantages and disadvantages of the AHP method.

Advantages	Disadvantages
• Hierarchical structuring of a decision problem • Combining multiple inputs from several persons to a consolidated outcome • Plausible results: people usually agree with the resulting priorities. • Calculation of results possible using Excel sheet	• Pair-wise comparison is an artificial way of comparing a set of items. • If consistency index is above 10%, then problems will arise requesting to reconsider inputs

Table 4, Outline of the main advantages and disadvantages of AHP

Table 5 shows Saaty's 9 point scale which is used by the decision makers when using the AHP method in order to compare the different alternatives in a given project in a pairwise manner.

Intensity of Importance	Invers of Intensity of the Importance	Definition	Explanation
9	1/9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
7	1/7	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
5	1/5	Strong importance	Experience and judgment strongly favour one element over another
3	1/3	Moderate importance	Experience and judgment slightly favour one element over another
1		Equal importance	Two elements contribute equally to the objective
2, 4, 6 and 8	1/2, 1/4, 1/6 and 1/8	When compromise is needed. Can be used to express intermediate values	
1.1, 1.2, etc.	1/1.1, 1/1.2, etc	Elements that are very close in importance	
Reciprocals		If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	
Rationales		Ratios arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix

Table 5, Fundamental importance scales in AHP (Chen et al., 2007)

2.7 Fuzzy Analytical Hierarchy Process (FAHP)

2.7.1 Fuzzy theory

The Fuzzy theory was developed by Professor Lotfi A. Zadeh, in 1965 (Zadeh, 1965) and it has been developed and used in many different fields since then such as control theory and artificial intelligence. Novák and colleagues mention in their book that Fuzzy logic is a complicated and very wide topic that deals with approximate rather than fixed and exact. Furthermore, they say that compared to traditional binary sets – where variables may be either 0 or 1 – Fuzzy logic deals with that exist within the 0 to 1 range (Novák et al., 1999).

In his book, Hanss said that “A fuzzy number is an extension of regular number in the sense that it does not refer to one single value but rather to a connected set of possible values, where each possible value has its own weight between 0 and 1. This weight is called the membership function. A fuzzy number is thus a special case of a convex, normalised fuzzy set of a real line” (Hanss, 2005).

2.7.2 Triangular Fuzzy Number (TFN)

Fuzzy numbers come in the form of different shapes. These shapes are Triangular, Trapezoidal and Bell Shape. Among these shapes, the Triangular shape is the most popular shape. TFNs are fuzzy numbers that are represented with three points as follows:

$$A = (a_1, a_2, a_3)$$

Equation 1, Typical triangular fuzzy number

As shown in figure 4 and equation 1, TFNs can then be interpreted as membership functions.

$$\mu_{(A)}(x) = \begin{cases} 0, & x < a_1 \\ \frac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2 \\ \frac{a_3 - x}{a_3 - a_2}, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases}$$

Equation 2, Triangular fuzzy numbers as membership functions

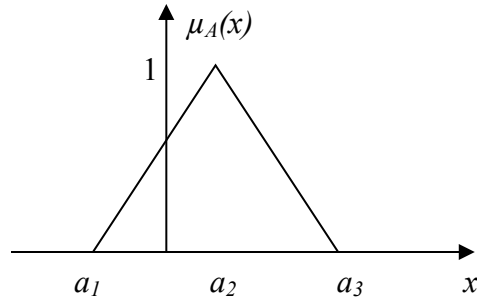


Figure 4, Triangular fuzzy number $A = (a_1, a_2, a_3)$

Chan et al. state that fuzzy numbers are intuitively easy to use in expressing the decision makers' qualitative assessments (Chan and Kumar, 2007). A fuzzy number can be shown by its left and right number within the membership function for the linguistic values expressed by the experts when using the FAHP method. A typical membership function is shown in figure 5.

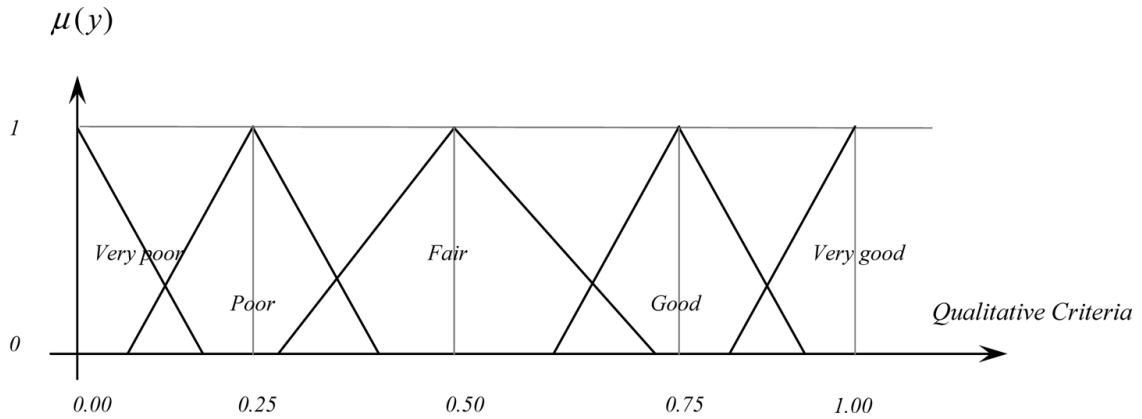


Figure 5, FAHP: membership function for linguistic values (Pan, 2008)

The AHP method – described in detail in section 2.6 of this thesis – is an effective method when it comes to solving problems with multiple criteria. However, there are also drawbacks to this method including the fact that it is unable to handle the inherent subjectivity and ambiguity that is associated with the experts’ perception to an exact number. According to Kahraman and colleagues, “although the AHP is to capture the expert’s knowledge, the traditional AHP still cannot really reflect the human thinking style” (Kahraman et al., 2003). The reason for this is that the AHP method uses an exact value to express decision makers’/experts’ pair-wise comparisons of the alternatives (Wang and Chen, 2007).

In this research project, the FAHP method is used in order to rank the different risks within the fault tree developed in chapter 4 (Methodology chapter). Similar to the conventional AHP method, the Fuzzy AHP method also involves the creation of a hierarchy that includes a set of alternatives, $M_i (i=1,2,\dots,m)$, criteria that are used for evaluation purposes, $C_j (j=1,2,\dots,n)$, and a final weighting vector, $w=(w_1, w_2 \dots, w_n)$ (Pan, 2008).

Furthermore, the pair-wise comparison matrices have to be converted to fuzzy pair-wise comparison matrices. In order to produce these matrices, the pair-wise comparison matrices that were used for the AHP method in section 2.6 of this chapter are going to be used. These matrices are created in the exact way that the AHP matrices are created.

This step involves the pair-wise comparison of the members of the decision making matrix. These pair-wise comparison matrices are created in order to determine the relative preferences of the alternatives with respect to each other. The structure of a generic pair-wise comparison matrix comparing the different alternatives of a decision is shown in equation 3.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad a_{ij} = \frac{1}{a_{ji}}, \quad a_{ii} = 1, \quad i, j = 1, 2, \dots, n$$

Equation 3, FAHP: Comparison matrix

The Consistency Index (CI) which evaluates the inconsistency of pair-wise comparisons is calculated using equation 4.

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Equation 4: FAHP: Consistency Index (CI)

where λ is an eigenvalue of matrix A and n is the number of columns. In addition, a Consistency Ration (CR) is calculated using equation 5.

$$CR = 100(CI / RI)$$

Equation 5: FAHP: Consistency Reaction (CR)

where CR is the consistency ratio, CI is the consistency index and RI is random index.

Furthermore, following the construction of the hierarchy, Chen and Yang's table (table 5) can be modified to accommodate the Fuzzy AHP technique which can be seen in table 6.

Intensity of Importance	Definition	Explanation
(8, 9, 10)	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
(6, 7, 8)	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
(4, 5, 6)	Strong importance	Experience and judgment strongly favour one element over another
(2, 3, 4)	Moderate importance	Experience and judgment slightly favour one element over another
(1,1,1)	Equal importance	Two elements contribute equally to the objective
(1,2,3); (3,4,5); (5,6,7) and (7,8,9)	When compromise is needed. Can be used to express intermediate values	
(0.1,1.1,2.1); (0.2,1.2,2.2) etc.	Elements that are very close in importance	
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix

Table 6, Fundamental fuzzy importance scales in FAHP

2.8 Justification for research techniques

The information gathered in this chapter, increases our knowledge concerning issues related to the risks associated with the storage of CO₂ underground and the ways in which these risks can potentially turn into hazards. However, evidence presented in the review of literature conducted, suggest that the majority of previous studies have analysed and assessed the risks associated with CO₂ storage from a qualitative point of view. In other words, there has been little effort to date in quantifying these risks so that a better understanding of the probability

and likelihood of different elements of the risks and the way in which they can be managed is gained (either individually or in conjunction with one another).

By improving this area of knowledge, this project aims to develop a framework in order to assist insurance bodies by providing them with the necessary scientific knowledge to be able to adjust their present terms and premium rates when insuring CCS projects against risks. Moreover, the findings of this project will help policy makers and regulators better tailor the legislation to address the risks associated with the CCS technology in general and more importantly the likelihood of them turning into hazards and their potential consequences.

According to the review of available literature, the methods used within this research, namely the FTA, AHP and FAHP techniques have not been widely used in combination with each other to quantify the risks involved in industrial scale projects such as CCS. Moreover, the said methods have neither been previously used in combination with each other within the CCS industry nor have they been used on an individual basis. However, they have been used widely on their own within other similar industries such as the nuclear, oil and gas and chemical industries.

The AHP method is an effective method when it comes to solving problems with multiple criteria. However, there are also drawbacks to this method including the fact that it is unable to handle the inherent subjectivity and ambiguity that is associated with the experts' perception to an exact number. According to Kahraman and colleagues, "although the AHP is to capture the expert's knowledge, the traditional AHP still cannot really reflect the human thinking style" (Kahraman et al., 2003). The reason for this is that the AHP method uses an exact value to express decision makers'/experts' pair-wise comparisons of the alternatives (Wang and Chen, 2007).

In order to find a solution to this matter, Buckley developed the Fuzzy Analytical Hierarchy Process (FAHP) method (Buckley, 1985). This method was then developed by many (Boender et al., 1989, Chang, 1996, Cheng, 1997, Barzilai, 1997, Chen, 2000, Hsieh et al., 2004, Gu and Zhu, 2006, Zeng et al., 2007, Wang et al., 2007) and different applications thereof have been used in many different sciences by different researchers (Büyüközkan et al., 2004, Cheng and Tang, 2009, Huang and Wu, 2005, Uberman and Ostrega, 2005, Aghajani Bazzazi et al., 2008, Naghadehi et al., 2009).

The conventional AHP method facilitates judgments and calculation preferences using pair-wise comparisons. Nonetheless, human judgments are commonly imprecise. Hence, the priorities are not determined by precise numeric amounts (Herrera and Herrera-Viedma, 2000). Zadeh developed the fuzzy theory in order to overcome imprecise judgments and preferences.

Since fuzziness and vagueness are common characteristics in many decision-making problems, an FAHP method should be able to tolerate vagueness or ambiguity (Mikhailov and Tsvetinov, 2004). In other words, FAHP is capable of capturing a human's appraisal of ambiguity when complex multi-attribute decision making problems are considered (Erensal et al., 2006).

2.9 Conclusion

In conclusion, the AHP and Fuzzy AHP methods that were used in this study, have worked in parallel to each other in order to provide consultation to decision makers within the field of CO₂ storage. This consultation will be in the form of relative importance and criticality of different risks that have been shown in the form of a fault tree diagram (figure 7).

Another point that has to be taken into account is that as mentioned before, these two methods are used in order to rank the risks that have been shown in the fault tree of this research project according to their importance and criticality from different perspectives using the output of the expert consultation stage. Therefore, decision makers need to use these results to suit their needs and hence make a decision that best suits their particular situation. For example, in one scenario (a scenario which makes use of one of the said methods), criterion 'A' carries 70% weight, criterion 'B' carries 20% and criterion 'C' therefore carries 10% of the total importance weight. In this case, one can clearly decide that criterion A is by far the most critical criteria (in case of the CCS industry, this would be the risk which has the highest probability of occurrence) followed by criterion 'B' and criterion 'C'. Therefore, in the case of an insurance body wanting to insure a particular CO₂ storage facility, most of their effort has to be put on criterion 'A' in order to manage the risks followed by criterion 'B' and 'C'.

On the other hand, in another scenario where another one of the said methods has been used, this combination of importance weights might be as follows: criterion A = 40%, criterion B = 39% and criterion C = 21%. In this case, criterion 'A' is still ranked as the most significant risk in terms of its potential negative effects on the environment. However, one cannot necessarily conclude that criterion 'B' is less significant than 'A' since this 1% difference might well be owing to the fact that the input parameters for the methods used in this study is based on the expert consultation stage and therefore are subjective and/or ambiguous and can potentially be inaccurate.

However, on the other hand, one must also take this into account that even though the methods described in this thesis have previously been used in a vast number of studies but they are still somewhat theoretical methods. In other words, in a given scenario, an alternative 'A' might be more advantageous and desired for a decision maker than alternative 'B'. However, alternative 'A' might not be a practical or financially feasible solution for the decision makers to implement in their projects.

The next chapter will present a methodological framework to identify, prioritise, assess and manage scenarios of risk to a large-scale system from multiple overlapping perspectives.

CHAPTER 3

LEGISLATIVE AND REGULATORY ASPECTS OF CCS

3 LEGISLATIVE AND REGULATORY ASPECTS OF CCS

3.1 Introduction

This chapter has been produced based on *Makuch, Z, et al, Carbon Capture and Storage in the United Kingdom, Imperial College Press, 2011*. “Carbon Capture and Storage in the United Kingdom” was produced as a result of a request from Scottish Power for Imperial College London to study the long-term liability of storing CO₂ in deep geological formations and the ways in which this liability can be addressed and dealt with.

Chapter 3 analyses the latest legislative and regulatory developments with regards to the CCS industry. The chapter falls into five sections. Firstly, the latest developments in CCS legislation and the underlying policy will be explored in section 4.2 followed by some potential forward looking scenarios. This chapter will then address specific risk-related financial and regulatory liability issues with regards to CCS. For example, there is discussion of the long-term liability of CO₂ storage sites that have been sealed off after injection has been completed. The ways in which the regulatory and legislative aspects of CCS are addressed in other jurisdictions and the lessons to be learned shall be discussed afterwards in section 4.5. Finally, the chapter compares the CCS industry with some other industries that are similar to CCS with regards to the type of risks involved in them, their likelihood and their potential effects on humans and the environment.

3.2 The latest developments in CCS legislation and underlying policy

3.2.1 Certain developments within the European Union

Since the passage of the CCS Directive, the following list of developments have occurred:

Report from the Commission to the Council and the European Parliament on the Implementation of the European Energy Programme for Recovery (EEPR) COM (2010) 191.

Findings include:

- Success of the call for proposals; high number and quality of the proposals received confirms the relevance of the EEPR approach and the readiness of industry.
- EEPR appears to have been an accelerator of infrastructure investments. Indeed, the technical maturity of the selected projects meant that pre-feasibility studies, cost and market analysis and investment strategies, in some cases funded by the TEN-E programme, had already been completed before the EEPR came into the picture.
- Perspective of the EU financial support for capital expenditure has proven to be decisive in the actual launching of the projects. EEPR funding has acted as a stimulus, attracting co-financiers and encouraging them to make investment commitments.
- CCS projects are making good progress. Demonstration effect is already being felt in the Rotterdam and Hatfield projects, which are aspiring to become CCS hubs with a potential to attract other investments for CO₂ transport and storage infrastructure from other big CO₂ emitters in the region. First orders for installations will be placed during 2010 and will lead to substantial capital expenditures and job creation.
- European Commission published four draft guidance documents on CCS with Guidance Document 4 Article 19 Financial Security and Article 20 Financial Contribution due to be finalised at the end of January 2010.

3.2.2 European Environment Agency Report (EEA)

The report presents an overview of all data that have been published in the National Renewable Energy Action Plans (NREAPs). Furthermore, the report covers 21 out of 27 European Member States and includes no specifics on plans for CCS projects.

3.2.2.1 Implementation of EU CCS Directive

The EU CCS Directive was transposed into national law on 25 June 2011 by Member States (in summary with detail to follow):

- Netherlands: A bill was before the Lower House in order to implement the CCS directive by amending the Mining Act. The bill focused mainly on the amendment of

Chapter 3 of the Mining Act. More specifically, the bill dealt with the embedding of CO₂ storage and ensured that the application process for a permanent storage licence is accessible to all entities that possessed the necessary capabilities. It did this by giving effect to other licences and protecting third-party access. Thus, Chapter 3 of the Mining Act is divided into two sections: one section with general provisions for the storage of substances, including CO₂; and the other with additional provisions that apply only to the permanent storage of CO₂.

- United Kingdom: Department of Energy and Climate Change (DECC) consulted on the UK implementation of the Directive at the end of 2009. The consultation document noted that applications for a CCS licence must provide proof of financial security for all the obligations arising from a storage permit and the insurance policies might be of the form of security. Insurers, including Lloyd's, have met DECC representatives to discuss insurance issues. DECC's response to the consultation, published in August 2010, noted that the liability issue requires a co-operative approach between Government, industry and the commercial insurance market. The development of products to satisfy the financial security requirement will be facilitated by the introduction of additional certainty around particular issues, such as maximum liability exposure and time periods. The European Commission finalised guidance on the Directive's financial security requirements in January 2011.

3.2.2.2 Developments in the UK connected to the transposition of the CCS Directive

3.2.2.2.1 *The UK Regulatory Response*

Legislative developments in recent times at European level have created a regulatory framework for offshore CCS within the European Community, whilst amendments to the London Protocol and OSPAR Convention to allow for sub-seabed geological storage, provide an international regulatory dimension. Whilst supporting the amendments to the London Protocol and OSPAR Convention in 2007, UK announced a competition for funding a full-scale demonstration project.

The Energy Bill was unveiled in 2008 which detailed a framework for the licensing, enforcement and registration of CCS. The Department for Business, Enterprise & Regulatory Reform (BERR) expected that the Bill would provide a sound system, which would enable

private sector investment in CCS projects and along with the Planning and Climate Change Bills, ensure legislation that underpins the long term delivery of the energy and climate change strategy. Creative legislative solutions in addition to the provision of finance will need to operate in tandem if first mover gains are to be won in the CCS field.

3.2.2.2.2 The Energy Act 2008

In summary, the Energy Review of 2006 concluded that should it be proved that CCS is cost-effective the next stage would need to be commercial demonstration. In Budget 2007, the Government announced a competition to design and build full-scale demonstration of CCS projects and it was launched in November 2007. The Energy Act 2008 established the enabling provisions for regulating offshore CO₂ storage in the UK in November 2008. Furthermore, consultation on the proposed offshore CO₂ licensing regime, including draft regulations to implement that regime was done in September 2009.

The Energy Act introduces a regulatory framework for the licensing of the offshore storage aspect of CCS. Furthermore, the Act states that there is a right of the Crown to the Exclusive Economic Zone (EEZ) which extends from the edge of the 12 miles of territorial sea for another 188 nautical miles in accordance with Part V of the United Nations Convention on the Law of the Sea 1982, in relation to the storing of gas. The Government may also designate 'Gas Importation and Storage Zones' within the EEZ. For operators seeking to undertake CCS activities within the newly designated EEZ, a lease and presumably a rental payment will be required from the Crown Estate. According to this Act, all natural resources belong to the coastal state including storage space under the sea bed.

A regime based upon licensing is introduced and requires a licence from the relevant authority for activities relating to the storage of CO₂ (with a view to its permanent disposal). These activities also include the conversion, exploration and maintenance of the 'controlled place' (site which may be found 'in, under or over' the territorial sea, or waters within a Gas Importation and Storage Zone). According to the Act, the Secretary of State grants a licence that may also attach a set of particular requirements for a specific applicant. The licence may include provisions relating to financial security in respect of future obligations, as well as obligations between the closure of an installation and the termination of a licence.

Furthermore, the Act introduces a detailed section about the enforcement of licences and criminal offences and sanctions in when activities are undertaken without a licence or where a licence holder fails to abide by its prescribed conditions. Inspectors may be appointed by the Secretary of State to assist with the inspection of such misconduct.

The Act applies Part 4 of the Petroleum Act 1998 (which concerns the abandonment of offshore installations) to carbon storage installations. The 1998 Act prescribes detailed plans and approvals that require persons seeking to abandon an installation offshore to provide an 'abandonment programme' which sets out the 'measures proposed to be taken in connection with the abandonment of an offshore installation or submarine pipeline'. Moreover, provisions are made for the licensing authority to formulate regulations with regards to the termination of licenses.

3.2.2.2.3 Energy Act 2010

The Bill implements elements of: *The UK Low Carbon Transition Plan – a national strategy for climate and energy*.

This Plan will deliver emission cuts of 18% on 2008 levels by 2020 (and over a one third reduction on 1990 levels) on the way to achieving a reduction of at least 80% by 2050. The Plan makes it clear that emissions need to be cut in a way that helps the sustainable development of the economy, society and environment. This means keeping energy supplies safe and secure, maximising economic opportunities and protecting the most vulnerable consumers.

- Carbon Capture and Storage and Decarbonisation

The Energy Act 2008 formed a financial incentive to support four CCS demonstration projects on power stations which were being powered by coal through a levy mechanism on electricity suppliers. In addition, according to the Act, the Government is required to prepare regular reports on the progress that has been made on the decarbonisation of electricity generation in UK and the development and use of CCS.

- Schemes for Reducing Fuel Poverty

The energy suppliers are forced by this Act to reduce the price of fuel for vulnerable consumers in order to reduce fuel poverty when the previous Voluntary Agreement with the energy suppliers ended in March 2011. A fundamental part of these schemes will be social price support which, subject to consultation, will come in the form of an electricity bill refund to certain groups of people that are more vulnerable in comparison with others.

- Regulation of Gas and Electricity Markets

This part of the Act clarifies the responsibilities of Office of Gas and Electricity Markets (Ofgem) with respect to climate change, protecting consumers and increasing energy security.

The Energy Act 2010 gives more authority to the Secretary of State to introduce a Market Power Licence Condition for electricity generators that will make it easier for Ofgem to address certain issues arising from the exploitation of market power where there are constraints on the amount of electricity that can be transmitted.

With respect to deadlines, the Act has changed the time limit that Ofgem can impose penalties for licence breaches from twelve months to five years.

Furthermore, this Act has given power to the Secretary of State to address situations where cross-subsidies between gas and electricity businesses lead to groups of consumers being disadvantaged.

Finally, the Act gives power to the Secretary of State to modify supply licences so that it can be made certain that suppliers will let their consumers know about any potential changes to their contract in terms of pricing or any other changes as such within a certain period of time.

3.2.2.2.4 *The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010*

These Regulations introduce a permitting regime for offshore CCS activities under the authority of Energy Act 2008. Furthermore, they set out a range of requirements that operators need to fulfil in order to obtain a storage site permit from the Secretary of State.

The Regulations do not cover licences granted by the Scottish Minister for Carbon Capture and Storage activities that are undertaken in the territorial waters adjacent to Scotland. In contrast, they do cover the conditions for granting licences and exploration permits, obligations of the storage site operator, closure of the storage site, post-closure period and financial security. Therefore, they only partially fulfil the UK's obligation to transpose the EU Directive on the geological storage of CO₂ (European Commission, 2009) into UK domestic law.

3.2.3 Regulatory Consultations to the UK

The list of regulatory consultations on CCS were as follows:

- Environmental Permitting: Consultation on further amendments to the Environmental Permitting (England and Wales) Regulations
- Consultation on the Proposed Offshore Carbon Dioxide Storage Licensing Regime
- Consultation on a framework for the development of clean coal

Those that appear to be most germane to this research are analysed below.

3.2.3.1 Environmental Permitting (EP)

Consultation on further amendments to the Environmental Permitting (England and Wales) Regulations 2010.

3.2.3.1.1 Introduction

The EP Regulations 2010 comprises a common set of definitions, processes and controls for the permitting of specified activities to prevent pollution. In doing so it has rationalised various permitting regimes into a common framework that is easier to understand and use. For example, it only requires businesses to have one permit instead of several permits for

activities falling under the regulations on one site and by doing so it allows the regulators to focus resources on activities with higher risks.

This consultation paper outlines four amendments to be made into the EP Regulations 2010 to take effect from 6 April 2011. The first two amendments arise from the need to transpose certain parts and provisions of the CCS directive. The third amendment is with respect to offshore CCS activities and the final amendment is regarding the gas produced by anaerobic digestion plants.

3.2.3.1.2 Regulatory Changes Proposed

- Amendment Required by the “Carbon Capture and Storage Directive”

The Government proposed (i) an addition to Part 2 of Schedule 1 to the EP Regulations 2010, and (ii) an amendment to paragraph 8 of Schedule 22 to the EP Regulations 2010 to transpose respectively Article 37 and 32 of the CCS Directive. Although the Directive’s transposition deadline was 25 June 2011, the Government considered that transposition some three months early will not add any regulatory burden. Rather, it will further clarify the regulatory framework for CCS and, through incorporation in a larger set of amending regulations, will reduce proliferation of regulations.

- Amendment in Respect to Offshore Carbon Capture and Storage Activities

The Government proposed an amendment to paragraphs 2 and 3 of section 1.1 (interpretation and application of Part A (1)) of Schedule 1 to the EP Regulations 2010 to avoid double regulation of offshore CCS activities.

- Amendment in Respect of Gas Produced by Anaerobic Digestion Plants

The Government proposed to remove from coverage by the activity description in Part A(1) of Section 1.2 of Part 2 of Schedule 1 to the Regulations the production of gas at AD plants treating biodegradable waste where that production is not part of a combustion activity.

3.2.3.2 Offshore Carbon Dioxide Storage Licensing Regime

3.2.3.2.1 Introduction

Carbon capture and storage is seen as an important technology when trying to reduce the CO₂ emitted from the industry and everyday life. Storing the captured CO₂ deep under geological formations is a crucial part of this process since it has to be made sure that the storage takes place at a place where the risk of leakage is minimal for the foreseeable future.

Accordingly, the Government has taken steps to provide a legal framework for the conduct of CO₂ storage operations in the UK. The Energy Act 2008 is promoted as one of the first legal regimes in the world specifically designed to permit the safe storage of CO₂ underground.

3.2.3.2.2 Regulatory Changes Proposed

Through the designation of a Gas Importation and Storage Zone (GISZ), the Government of the UK has applied the terms of the United Nations Convention on the Law of the Sea in order to assert certain rights to make use of the offshore area beyond the territorial sea. This Act also provides for a regulatory regime for CO₂ storage in the UK offshore area and for certain relevant existing offshore oil and gas legislation. For example, the decommissioning regime of Part IV of the Petroleum Act 1998 will be applied to facilities used for CO₂ storage.

In this document, DECC is proposing ways in which the licensing regime proposed by the government for these activities is going to be introduced. It further shows how they are going to implement the CCS Directive. Furthermore, the supporting consultation document sought to build on earlier work by setting out a proposed licensing framework under the powers of the Energy Act, which would be embodied with regulations transposing the Directive into UK law. The licensing regime for CO₂ storage is meant to cover an area of up to 200 nautical miles from the baselines of the territorial sea (throughout the GISZ and the area of territorial sea).

Under the provisions of the Food and Environment Protection Act (FEPA) License, the Scottish Ministers and the Secretary of State have in turn the regulation making, licensing and enforcement powers in relation to CO₂ storage sites located in the territorial sea adjacent

to Scotland and the remainder of the relevant UK waters respectively. Regarding the Welsh and Northern Ireland territorial sea, the devolved administration has elected to retain their FEPA consenting powers.

The licensing regime will regulate storage in depleted and partially depleted hydrocarbon fields under the sea bed and in non-hydrocarbon geological features such as deep saline aquifers.

The Government intended to set down the regulations in the first quarter of 2010 in order to bring the regime into force in April 2010 (subject to the outcome of its consultation around the regulations).

This document outlines what developers need to do in order to obtain a licence to undertake all the activities involved in a project as such. These activities include the exploration stage, storage site development, storage site operation and storage site closure.

- Liability Implications

The proposed license is very similar to the licences granted to the petroleum production industry. The licence – subject to specific consent for drilling of any well – permits the conduction of intrusive exploration. Furthermore, it also expresses time limited rights to apply for storage permits which allows site operators to construct storage facilities – including offshore storage facilities – in order to store the liquefied CO₂. Moreover, the licence provides the necessary framework to demonstrate the legal obligations that site operators have with respect to ensuring the safe/secure containment of CO₂ under geological formations, decommissioning the site after use and the monitoring of the stored material's behaviour during and after the completion of storage operations.

3.2.3.3 Planning for New Energy Infrastructure: Consultation on Revised Draft National Policy Statements for Energy Infrastructure

3.2.3.3.1 Introduction

Historically, national policy planning and implementation for major infrastructure has proven to be a real challenge. It is anticipated that this may also be the case for CCS infrastructure

including a complex and evolving network that will integrate capture, pipeline and storage features. The latest effort to plan for the delivery of similar infrastructure comes by way of the National Policy Statements for Energy Infrastructure consultation. It is believed by the author that it would be wise to take the planning and lessons of this process and apply them to the development of CCS infrastructure in the UK. For this reason, information and analysis in relation to the National Policy Statements (NPS) for Energy Infrastructure have been included in this thesis.

Accordingly, the Government wants a planning system for major infrastructure which is rapid, predictable and accountable. Planning decisions should be taken within a clear policy framework making these decisions as transparent as possible. The energy NPSs will be a blueprint for decision-making on individual applications for development consent for the relevant types of infrastructure.

Between November 2009 and February 2010, the previous Government consulted six draft energy NPSs and the Appraisal of Sustainability (AoSs), Habitats Regulations Assessments (HRAs) and Impact Assessment that accompanied those NPSs. Over 3000 responses were received and this document identifies the key themes and responds to them.

This document has been produced as a result of a re-consultation that had to be made owing to the fact that the Government made changes after receiving the responses to the original consultation and having considered the outputs of the Parliamentary scrutiny process.

3.2.3.3.2 Regulatory Changes Proposed

According to the Government, the most important changes that this document has undergone are:

- Reconsideration of the alternatives: The selection and appraisal of policy alternatives within the AoSs for EN-1 to EN-5 have been reconsidered. New alternatives have been developed and appraised. This means that the likely impacts of consenting new energy infrastructure in accordance with the policies set out in these NPSs should be clearer.

- Need for the infrastructure: This section sets out the need for new energy infrastructure and has been updated to take account of the latest modelling and Pathways to 2050 work. The changes are reflected in EN-1 which is where the need for individual technologies also now appears.

3.2.3.3.3 Potentially Suitable Sites

Potentially suitable sites for nuclear power station development: Kirksanton and Braystones in Cumbria have been removed from the list of potentially suitable sites within EN-6 whereas Dungeness in Kent remains off the list.

As regards the next steps for draft energy NPSs, the Government intends to finalise and then formally designate and adopt the energy NPSs (subject to this consultation) in 2011. Furthermore, once they have been designated, the energy NPSs will be the primary consideration for the IPC when it makes decisions on applications for development consent for nationally significant energy infrastructure under the Planning Act 2008.

Listed below, are the different points that have been changed in the revised version of the consultation document:

- Revised draft Overarching National Policy Statement for Energy (EN-1)
- Revised draft National Policy Statement for Fossil Fuel Electricity Generating Infrastructure (EN-2)
- Revised draft National Policy Statement for Renewable Energy Infrastructure (EN-3)
- Revised draft National Policy Statement for Gas Supply Infrastructure and Gas and Oil Pipelines (EN-4)
- Revised draft National Policy Statement for Electricity Networks Infrastructure (EN-5)
- Revised draft National Policy Statement for Nuclear Power Generation (EN-6)
- Revised Appraisals of Sustainability for EN 1-5
- Revised Habitats Regulations Assessments for EN 1-5
- Revised Appraisals of Sustainability for EN-6 (the revised draft Nuclear National Policy Statement)

- Revised Habitats Regulations Assessments for EN-6 (the revised draft Nuclear National Policy Statement)
- Revised Impact Assessment

3.2.3.3.4 Looking Forward

“A framework for the development of clean coal” was published in November 2009 committing the UK to 4 commercial scale demonstrations of CCS, funded through a financial incentive and setting out the regulatory policy for the consenting of new coal fired power stations in England and Wales. The framework prohibits the construction of new coal fired power stations without the demonstration of CCS and sets out plans for the long-term transition to clean coal.

Detailed provisions concerning the financial incentive mechanism was laid in regulations (spring 2011).

The framework also refers to the implementation of the EU Directive on the geological storage of CO₂ in the UK, including:

- Regulations and guidance on offshore storage of CO₂ (autumn 2010).
- Regulations for third party access to CO₂ pipelines and storage sites (December 2010).

3.3 Forward looking scenarios

3.3.1 UK Policy and Regulatory Milestones for the Future

In this section, key policy and regulatory milestones have been identified within which carbon capture and storage facilities are meant to be developed.

3.3.1.1 Scottish Policy and Regulatory Milestones for the Future

3.3.1.1.1 Important Milestones

If CCS is to have a significant contribution in reducing CO₂ emission, the milestones listed below have to be met by 2030.

- **2015-2020:** Globally, 20 CCS projects should exist, of which 8 of them should be demonstrated by the EU. Furthermore, 4 of these demonstration projects should be situated in the UK and Scotland should at least have 1 share (or more) of these demonstration projects. Overall, the EU should be able to store 30 million tonnes per year CO₂ (Scottish Government and Scottish enterprise, 2010).
- **2020:** By 2020, the EU is expected to be able to cumulatively store 150 million tonnes of CO₂. Furthermore, the EU and UK should start deploying CCS. There would also be a need for large scale proven aquifer storage capacity. There would be a need for a financial funding method for CCS deployment established (Scottish Government and Scottish enterprise, 2010).
- **2020-2030:** CCS changes from demonstration to deployment phase and CCS rollout (Scottish Government and Scottish enterprise, 2010).

3.3.1.1.2 Legal and Regulatory Milestones

The Scottish Government has seen the following regulatory changes as necessary in order for CCS to become a reality in Scotland.

- 2009-2010: The development of offshore carbon licensing regime (2009-2010); Working with UK government on funding mechanisms for generation (2009-2010) (Scottish Government and Scottish enterprise, 2010).
- 2010-2015: OSPAR and London Convention ratified to allow cross border; Details on electricity levy mechanism to facilitate CCS demonstration projects; Amendment to regulations to allow CCS as an activity to gain Pollution Prevention and Control (PPC) permitting regime (Scottish Government and Scottish enterprise, 2010).

- 2015-2029: Money from levy has been deployed for demonstration projects; Continued refinement of regulatory approach especially in relation to storage (Scottish Government and Scottish enterprise, 2010).
- 2030: Clear approach on regulation with reward to all aspects of the CCS chain (Scottish Government and Scottish enterprise, 2010).

3.4 Addressing Specific Liability Issues

In this section, some of the pressing legal and regulatory issues and their interpretation in the context of the CCS industry have been addressed.

In addition to stating what is covered, a question is also raised that is beyond the scope of this research save for a few remarks. However, it deserves greater attention in future research. It concerns state aids law application to CCS. This question is as follows: Given the current uncertain and uncapped nature of liability in relation to CO₂ stream storage sites, the primary objective of CO₂ storage is not to provide a solid business opportunity for investors. Instead CO₂ storage is essentially providing a public interest function aimed at satisfying climate change mitigation and therefore addresses legislated targets placed upon Member States of the EU. Given this public interest function, it is logical to ask whether state aids restrictions on financial incentives for CCS apply given that state aids rules do not apply to the delivery of public interest legislation by Member States. It would appear, at least that subsidies provided for advancing commercial scale CCS plants have not attracted such attention as they are permitted further to the financing mechanism of the Emissions Trading Directive.

Wilson et al. note that creating a liability regime for CCS must strike a balance between risks and benefits of technology and this could influence the deployment of CCS. They argue that the certainty, clarity and extent of legal liability could affect technology adoption, or specifically new technology deployment. Companies considering the adoption of a new technology may be deterred by uncertain or potentially unlimited liabilities associated with technological problems new to industrial scale (Wilson et al., 2009).

Legal liability is critical for the government and regulatory authorities to promote adoption of CCS technology as it helps ensure a party with the highest information on the risks and

solutions to those risks take the appropriate measures to avoid adverse consequences (Selmer-Olsen, 2006). In addition, transparent and clear liability system enhances the ability of the public to understand the risks and have confidence that these risks to the human health and the surrounding environment are being actively managed and in case an accident happens, it will be effectively remediated and they will be adequately compensated (Selmer-Olsen, 2006). Under the CCS Directive and ETS, the liabilities associated with CO₂ exposure deal with the impacts of CO₂ to climate change in case it leaks to the surface. This therefore calls for the companies to continuously monitor and evaluate the storage site to ensure that they take appropriate actions to prevent leakage of CO₂ throughout the system (Haan-Kamminga et al., 2010).

These liabilities deal with the measures that should be adopted by the companies to protect human health and the environment. Currently, regulations for underground injection only address the operational phase and fail to specify future monitoring and risk management issues (Wilson and Gerard, 2007). Wilson and Gerard explain that when the storage site gets to its storage capacity, it is critical to implement to close up the site and monitor the site to ensure that the injected CO₂ remains there.

According to Figueiredo et al., liability for carbon capture and storage can be looked from the operational liability and post-injection liability (de Figueiredo et al., 2006). At the operational stage, liability includes the environmental, health and safety risks involved in the capture of CO₂, transportation and injection. Post-injection liability in CCS refers to the liability that comes up in the storage of CO₂ after its injection into the geological reservoir (Zheng et al., 2009). Carbon capture liability during the storage stage can either be in-situ liability or climate related liability.

In-situ liability results from the potential risks of harm to the environment, human health and property. Climate related liability on the other hand deals with liability arising from the leakage of CO₂ from geological reservoirs and the resulting impacts to the climate (de Figueiredo et al., 2006). Climate liability is a function of the international and national policies formulated to address greenhouse gas emissions. Post-injection liabilities present unique challenges given that the projected CO₂ volumes to be stored in geological reservoirs are very high; 103-590 GtC between 2000 and the year 2100 (de Figueiredo et al., 2006). Moreover, the risks of CO₂ leakage may take long before manifesting themselves and there

are uncertainties in the geophysical system. Given the above challenges, a private liability may not be effective in addressing the risks of CCS (Durrant, 2011).

As time passes, the risks associated with the CO₂ stored in geological reservoirs could be reduced and as a result the safety could increase owing to geochemical and geophysical trapping (Ha-Duong and Keith, 2003). When liability is fully placed on the private sector, the potential unbounded liability can make deployment of CCS unlikely. On the other hand, when the public sector is made to bear the liability for any future leakage, this can potentially affect the safety measures taken by companies in the near term (Ha-Duong and Keith, 2003).

Leakage of CO₂ – which is the main risk associated with CCS – can either occur into the surface or subsurface. However, some argue that the most probable cause for loss of containment is neglected wells. Furthermore, they suggest that properly-designed reservoirs have the ability to contain CO₂ long after they have been abandoned. Figueiredo et al. observe that poorly completed reservoirs are more likely to lead to CO₂ escaping into the atmosphere. On the other hand, some suggest that another way CO₂ can be released is for it to leak via pores of low-permeable caprocks when the injection is done at high pressure (de Figueiredo et al., 2006).

Figueiredo et al. note that there are five categories of risks resulting from CO₂ storage liability. These include toxicological effects, environmental effects, subsurface trespass, induced seismic actions and effects on the climate. Toxicological effects are directly related to the concentrations and period of exposure. The liability related to climate risk is basically a contractual liability for non-performance (de Figueiredo et al., 2006). Compensation to victims in an event of risk may be difficult given that CO₂ can remain in the ground for too long before it escapes and by then the companies responsible may have been out of business. Consequently, seeking for compensation for such risks may be difficult given that the afflicted would have to identify defendants. Moreover, even when the defendants are identified, afflicted parties may experience difficulties in demonstrating the particular causation or that the storage site of the defendant is responsible for causing the injuries suffered.

3.4.1 Liability for a Release of Stored CO₂ under the ETS and CCS Directives

According to Recital (30) of CCS Directive (which is not binding but is to be treated as informing the purposive interpretation of the CCS Directive):

“Provisions are required concerning liability for damage to the local environment and the climate, resulting from any failure of permanent containment of CO₂. Liability for environmental damage (damage to protected species and natural habitats, water and land) is regulated by Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage (1), which should be applied to the operation of storage sites pursuant to this Directive. Liability for climate damage as a result of leakages is covered by the inclusion of storage sites in Directive 2003/87/EC, which requires surrender of emissions trading allowances for any leaked emissions. In addition, this Directive should establish the obligation on the operator of the storage site to take corrective measures in case of leakages or significant irregularities on the basis of a corrective measures plan submitted to and approved by the competent national authority. Where the operator fails to take the necessary corrective measures, these measures should be taken by the competent authority, which should recover the costs from the operator.”

Aside from the recital above, the CCS Directive itself does not address the question of liability. Hence, we must look to the Environmental Liability Directive and the Emissions Trading Scheme Directive given that the CCS Directive delegates this matter to them.

Further to Article 34 of the CCS Directive, the Environmental Liability Directive brings storage site operations within the liability framework of the European Union. As such, operators of CCS sites have obligations in respect of the prevention and remediation of environmental damage associated with such sites. Financial security measures are also to be undertaken by storage site operators further to Article 14. A flexible interpretation of Article 14 allows for the use of ceilings on financial instruments. It also allows for the exclusion of liability on behalf of operators, where they are not at fault or are otherwise not negligent. Finally, in respect of exclusions from liability a CCS operator will not be liable for environmental damage or the imminent threat of damage in relation to a natural phenomenon of exceptional, inevitable and irresistible character.

As the CCS Directive is without its own liability provisions¹, the Environmental Liability Directive language pertaining to the definition of “environmental damage” and corresponding duties of prevention (Article 5) and remediation/mitigation (Article 6) should be determinative in this regard². As such it is of great importance to the determination of liability particularly when one notes in respect of Article 4 exceptions from liability that seismic events or tectonic plate shifts resulting in environmental damage would give rise to no liability to the operator Article 4 (1) (b).

In the context of the Emissions Trading Directive, arguably, as environmental damage that might arise from a CO₂ leak would include environmental damage in a climate change context, such events or shifts would give rise to no liability to any party and as such allowances would not be required to be purchased to make up for the leak. On a related note, where climate change mitigation and prevention efforts that have as their goal the prevention of impacts to land, water, species or their habitats as covered by the Environmental Liability Directive and they are compensated for in relation to a leak then they should not be the subject of further emissions allowance surrenders as these will have already been compensated for under the Environmental Liability Directive.

¹CCS Directive Article 28 penalties may be designed to punish non-compliance with the Directive however, the consequences for environmental damage (i.e., liability for environmental damage) are addressed through delegated legislation through Article 34 which draws environmental liability in the CCS sphere into the Environmental Liability Directive

²According to the Environmental Liability Directive "environmental damage" means: (a) damage to protected species and natural habitats, which is any damage that has significant adverse effects on reaching or maintaining the favourable conservation status of such habitats or species. The significance of such effects is to be assessed with reference to the baseline condition, taking account of the criteria set out in Annex I;

Damage to protected species and natural habitats does not include previously identified adverse effects which result from an act by an operator which was expressly authorised by the relevant authorities in accordance with provisions implementing Article 6(3) and (4) or Article 16 of Directive 92/43/EEC or Article 9 of Directive 79/409/EEC or, in the case of habitats and species not covered by Community law, in accordance with equivalent provisions of national law on nature conservation.

(b) water damage, which is any damage that significantly adversely affects the ecological, chemical and/or quantitative status and/or ecological potential, as defined in Directive 2000/60/EC, of the waters concerned, with the exception of adverse effects where Article 4(7) of that Directive applies;

(c) land damage, which is any land contamination that creates a significant risk of human health being adversely affected as a result of the direct or indirect introduction, in, on or under land, of substances, preparations, organisms or micro-organisms;

Further to this point, it has been noted that the purchase of emissions credits serves as a climate change mitigation and prevention strategy in itself and that damage in terms of failed climate change mitigation is already covered in respect of the types of damage listed in the EU Environmental Liability Directive (2004/35/EC) including, but not limited to species loss, marine ecosystem damage, fundamental changes in land use, damage to land, damage to water, etc. If CCS operators are legally required to buy emissions credits and CCS operators also bound to cover liability of the same leakage event, there is a clear double-payment by the private sector. Therefore, this problem of double-counting liability has to be addressed by regulatory solutions that push forward CCS technology investment.

In reference to the ETS Directive, from 2013 captured CO₂ will be considered as non-emitted (see Recital 39 of ETS Directive).

If, despite the precautions taken in selecting a site, it does leak in practice, it is suggested that corrective measures must be taken to rectify the situation and return the site to a safe state. A review of the ETS Directive as amended suggests that emissions trading allowances would need to be surrendered for any leaked CO₂ to compensate for the fact that the stored emissions were credited under the ETS as not emitted when they left the source. On the basis of the discussion in this sub-section, the treatment of emissions allowances in the event of a leak is in terms of the amounts to be surrendered and the distribution of responsibility for the purchase and surrender of the said allowances.

3.4.2 Liability at Carbon Dioxide Storage Facilities

Geological storage will extend over much longer periods than the lifespan of an average commercial entity. Arrangements are needed to ensure the long-term stewardship of storage sites. The CCS Directive (Article 32) thus provides for sites to be transferred to Member State control in the long term. However, arguably, the polluter pays principle requires that the operator retain responsibility for a site while it presents a significant risk of leakage. Also, rules are needed to ensure that no distortion of competition arises from different Member State approaches.

Furthermore, under the Article 33 of the Directive, a storage site shall be transferred (including legal liabilities) to the state when 1) all available evidence indicates that the CO₂ will be completely contained for the indefinite future, 2) a minimum period before transfer to be determined by the competent authority has elapsed, 3) a financial contribution for the post-transfer period covering at least the costs for monitoring for 30 years has been made and 4) the site has been sealed and the injection facilities have been removed. As this is the second key decision in the lifecycle of a storage site (the first being the decision to permit the site for use), a Commission review is foreseen at this stage too.

3.4.3 Costing and Attribution of Liability for Surrendered Allowances under the ETS Directive

In theory, emissions trading allowances must be surrendered for any leaked CO₂, in order to compensate for the fact that the stored emissions were credited under the ETS as not emitted when they left the source. However, questions arise as to the applicability of the surrender requirement noting that ETS itself does not have a surrender requirement attached but an exemption in respect of stored CO₂. Equally, if for argument sake a leak occurred during a relevant Phase of ETS when allowances could be purchased to address storage taking place in that phase then this may be a more straightforward compensation issue. There is a greater likelihood of leakage in a long term storage scenario which may occur many phases after the phase in which the leaked CO₂ was first stored. Against this scenario, the application of the ETS to a leak is less clear.

CCS Directive Guidance Document 4 provides further insight into this question. However, the proposed assumptions and calculation methods yielded in the document would appear to be highly speculative in estimating leakage *ab initio*.

As summarised below, in respect of the surrender of allowances, there is the argument that by virtue of the inclusion of geological storage sites under Annex I of the Emissions Trading Directive, installations will be required to surrender allowances for any emissions from the site, including leakage, as calculated pursuant to the Monitoring and Reporting Guidelines for CCS (forthcoming). The amount of the FS for this obligation can be based on the potential total tons of emissions, including due to leakage(s), multiplied by the market cost of

purchasing an equivalent amount of allowances. This calculation will require (1) estimates for the total tons of emissions that may be released, including due to leakage(s), (2) the timing of emissions, and (3) costs of allowances when releases occur.

In the absence of experience with geological storage of CO₂, determining an appropriate amount of FS for surrender of allowances can be based on different assumptions concerning the amounts of potential leakages of CO₂. Options can include calculating the amount based upon:

- A conservative estimate of the maximum portion of CO₂ that can be released from storage, which, in most situations, will be much less than 100%;
- Best case assumption that only a small portion (e.g., 1%) of the CO₂ is released.

The initial amount of FS for surrenders of allowances should be based on the potential for leakages during (1) the operator's anticipated period of injections (e.g., 20 years, 30 years, 50 years) plus (2) the expected duration of closure activities, and (3) the minimum period of years for post-closure determined by the CA. Periodic updates to the FS may reflect other assumptions about potential amounts of leakages as more evidence on the site and storage behaviour is gathered.

The timing of leakages is important to determining the amount of FS because the EU Allowances (EUA) price is determined on the carbon market.

There is unavoidable uncertainty about the future price of EUA at the time of any potential leakage. There is no cap on the EUA price; the penalty for excess emission (100 Euros per tonne) does not relieve the operator of the need to provide allowances to cover the emissions, and is not therefore a cap on EUA prices.

Beyond this uncertainty, other practical and legal issues arise. These are detailed in the remaining paragraphs of this sub-section.

The requirement to reimburse CO₂ emitted as a result of the leak from a CO₂ storage facility is problematic in view of the uncertainty about the future rules (if not the future of the Scheme in the coming decades) that might apply to emissions allowances under the EU (and therefore UK) emissions trading system. At this point, we simply do not know what international context will exist beyond the Kyoto Protocol and its extension agreement, nor

do we know whether any rule changes to impact upon the shelf life of emissions allowances are the period to which they would have to be applied.

Carbon capture facilities and CO₂ storage facilities will not be required to surrender emissions allowances, where CO₂ is transported and stored in a permanent facility could not hedge against market uncertainty in respect of future carbon prices, because a leak is more likely after the operational phase of a carbon capture and storage facility. This may well be in the distant future. This is problematic because emissions allowances tend to have a shelf life for the (average four-year) phase in which emissions occur. Certain types of emissions allowances can be carried over to the next phase. However, any leak in the post operational phase of a carbon storage facility would occur well past this second phase.

The need to hedge against such risk becomes important when it is likely that liability for allowances would entail greater costs over time as carbon prices rise. From an economic point of view, when considering the position on indemnification of allowances at some future date, it would be cheaper for energy producers to purchase emission allowances in contrast to investing in a technology that has significant upfront installation costs and significant investment costs for a long term liability which may well not ever materialise.

Furthermore, the assumption for long-term emissions credits liability would mean that allowances which are bought in the future, as a compensatory measure for loss of CO₂ stored, would be with a significantly higher price tag than those bought today which would further defer investments. This is especially true as readily available primary resources of energy are in global decline and the price of bringing energy to market is steadily increasing. If the EU wishes to increase investment in low-carbon and renewable technologies, it would also be assumed to favour environmental cost internalization and a subsequent higher pricing of traditional forms of energy in order to enhance the competitiveness of renewables. These likely trends in relation to a higher carbon price would result in the payment of future allowances many times the value of those purchased that might be purchased at a date closer to carbon capture plant deployment and would thus significantly disincentivise CCS deployment.

It is also unlikely that the shelf life of emissions allowances will be extended in view of the requirement under the so-called Commitment Period Reserve (CPR) which requires States to ensure that 90% of their assigned emissions reduction amount or five times the States was

recently reviewed inventory, must be constantly held as valid units and allowances. Noting that as climate-change related damage increases and so to the cost of mitigation it is likely that carbon prices will rise and there will be less likelihood of carrying over allowances for extended periods of time. In part, this conclusion is made on the basis that States – and the private sector entities that they regulate – will be subject to greater scrutiny for regularised reduction trends as climate change-related damage ramps up and becomes more obvious to members of civil society.

If the requirement to surrender allowances were to occur at some point in the distant future then this compounds certain other technical challenges. It is to be noted that a number of firms will provide carbon streams to any given storage site. A question would arise as to which carbon stream provider should assume responsibility and in what proportion for any given leak. It may well be that certain carbon stream providers will argue that the “leaked” CO₂ did not include at least some CO₂ from their specific carbon stream and there may be grounds for the technical argument that a leak in a reservoir at the opposite end of the initial injection point would constitute a leak of CO₂ from early (rather than the latest) carbon stream provision to the storage site, noting that there is a time window before which carbon stream mix and composition become uniform within a storage reservoir. Apportioning “emission allowance surrender” responsibility to individual private-sector carbon stream providers in those circumstances, would be particularly challenging.

This problem is compounded still further by the evident conflict that may arise in relation to apportionment of “emission surrender allowance” liabilities as between carbon stream providers and carbon storage sites (both parties are regulated under the amended ETS). In such circumstances, it is worth noting that the recipients of the exemption from surrendering allowances in respect of the revised Article 3A of the ETS Directive would be those that have captured and transported the emissions for permanent storage. As exemption beneficiaries, their contribution to an “emission allowance surrender” where they have provided a CO₂ stream to the storage site at which a leak has occurred would need to be considered.

Finally, another level of complexity in “emission surrender allowance” appears by reference to Draft Commission Decision amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of CO₂. This reporting guidance suggests monitoring and reporting for

leakage in respect of three specific activities namely, capture, transport and storage, that are regulated through the following Annexes of the Draft Decision:

- Annex XVI – Activity-specific guidelines for determination of greenhouse gas emissions from CO₂ capture activities for the purposes of transport and geological storage;
- Annex XVII – Activity-specific guidelines for determination of greenhouse gas emissions from the transport of CO₂ by pipelines; and,
- Annex XVIII – Activity-specific guidelines for the geological storage of CO₂ in a storage site

As capture facilities, transport networks and storage facilities may well be separately owned and controlled, then each firm could have some responsibility for leakage and, therefore, the costs of emission surrender allowance-related purchases.

It is this line of analysis which is as perplexing as the long term liability implications for storage site operators under the Environmental Liability Directive. Indeed, this double liability for environmental damage, which is covered by two liability regimes for one event (i.e., one leakage event), requires sophisticated policy and legislative drafting skill and attention. Otherwise, the long term liability risks and uncertainties will significantly outweigh any benefit of private sector participation in CCS as a public interest climate change mitigation strategy.

In conclusion, the proposed methodology for addressing leakage as indicated in the Commission Guidance document is without a sufficient technical basis to be reliable for prospective investors and other private sector analysis. This is why the following preferred line of argumentation is taken.

By way of reviewing the legislative groundwork, further to the ETS Amending Directive, there is a new Article 12 (3a) which states that allowances are not required to be surrendered for emissions verified as captured and transported to a storage facility.

Article 19 of the ETS Directive requires set up of an Emission Trading Registry for issuing, holding, transferring and cancelling allowances. This mechanism assists in the determination of allowances to be surrendered by an ETS-regulated installation on an annual basis.

It is unlikely that allowances to be surrendered in the event of a leak perhaps a decade or decades after start-up of CO₂ stream transport to storage sites would be visited upon a power company with a carbon capture site (regulated under ETS) many years after the phase in which that site began transport of a carbon stream to a storage facility.

For this reason and noting the number of risk management measures available to competent authorities under the CCS Directive and storage site operators by way of their evolving technical know-how, the requirement that storage sites be selected on the basis that they will not leak all suggest that CO₂ stream providers and storage site operators should make no provision for allowance purchases to account for a hypothetical leak. Such a purchase should only be made if required by evolving law, whatever that may be, noting the leakage is more likely in the post-operational period of a storage site.

3.4.4 Leakage after Site Closure or the Cessation of Carbon Dioxide Storage: Handover to the Government

In advance of the grant of a permit, a detailed analysis of the potential site must be carried out according to criteria specified in Annex I of the CCS Directive, including modelling of the expected behaviour of CO₂ following injection. The site can be used only if this analysis shows that under the proposed conditions of use there is no significant risk of leakage, and that no significant health or environmental impacts are likely to occur. This gives the competent authority considerable comfort over the risks and risk management measures that might attend a prospective site as it cannot be approved unless the competent authority is satisfied that the prospective site will not leak.

The initial analysis of the site is done by the potential operator, who then submits the documentation to the Member State competent authority in the permit application. The competent authority reviews the information and if it is satisfied that the condition is met, issues a draft permit decision financing of the demonstration projects.

In relation to site closure, the responsibility for the storage site, including specific legal obligations, should be transferred to the competent authority, if and when all available evidence indicates that the stored CO₂ will be completely and permanently contained. To this

end, the operator should submit a report to the competent authority for approval of the transfer. This suggests that in the eventuality of the CO₂ leaking afterwards, the liability is transferred from the operator to the competent authority.

As the basis upon which the decision to transfer control of the storage site to competent authority could be made more clear, it is important for the competent authority to be more methodologically specific in this regard with respect to its national legislation. This will create more certainty around investment-related risk decisions as the failure to be more specific will leave significant subjective discretion for the competent authority to decide when complete and permanent containment of CO₂ has occurred. Other jurisdictions are already much more specific in this regard.

3.4.5 *International Law*

In respect of the international law pertaining to CCS, the London Dumping Convention (LDC) and the OSPAR Convention and their legal instruments are given treatment in this sub-section with appropriate conclusions provided for each regime.

3.4.5.1 International Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Dumping Convention)

The operative provisions of the London Dumping Convention as they pertain to CCS are as follows:

- Article 3: Dumping does not include: placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of the Convention (IMO, 1972).
- Article 4: Dumping of wastes or other matter listed in Annex 1 prohibited, Annex 2 requires a special permit. Others require a prior general permit (IMO, 1972).
- Article 6: Each Contracting Party shall designate appropriate authorities to issue special permits for Annex 2 substances or other unlisted matter. They are also to keep records and monitor the state of sea (IMO, 1972).

- Article 10: In accordance with the principles of international law regarding State responsibility for damage to the environment of the other States or to any other area of the environment, caused by dumping of wastes and other matter of all kinds, the Contracting Parties undertake to develop procedures for the assessment of liability and the settlement of disputes regarding dumping (IMO, 1972).
- Article 12: Contracting Parties pledge themselves to promote, within the competent specialised agencies and other international bodies, measures to protect the marine environment against pollution caused by:
 - (a) hydrocarbons, including oil, and their wastes;
 - (f) wastes or other matters directly arising from, or related to the exploration, exploitation and associated off-shore processing of sea-bed mineral resources (IMO, 1972).

Annex I

Annex does not apply to substances which are rapidly rendered harmless by physical, chemical or biological processes in the sea provided they do not:

1. make edible marine organisms unpalatable, or
2. endanger human health or that of domestic animals.

3.4.5.2 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972, Entry into force: 4 March 2006.

In essence, dumping is prohibited, except for materials on an approved list. This contrasts with the 1972 Convention which permitted dumping of wastes at sea, except for those materials on a banned list. In respect of a review of the compatibility of CO₂ capture and storage in sub-seabed geological structures, as part of a suite of measures to tackle the challenge of climate change and ocean acidification the precautionary approach is stressed. The 1996 Protocol introduces (in Article 3) what is known as the "precautionary approach" as a general obligation. This requires that appropriate preventative measures are taken when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation

between inputs and their effects (IMO, 1972). The article also states that the polluter should, in principle, bear the cost of pollution and it emphasizes that Contracting Parties should ensure that the Protocol should not simply result in pollution being transferred from one part of the environment to another (IMO, 1972).

The 1996 Protocol states (in Article 4) that Contracting Parties "shall prohibit the dumping of any wastes or other matter with the exception of those listed (IMO, 1996)" (in Annex 1 to the Protocol). These materials include:

- Dredged material
- Sewage sludge
- Fish waste, or material resulting from industrial fish processing operations
- Vessels and platforms or other man-made structures at sea
- Inert, inorganic geological material
- Organic material of natural origin
- Bulky items primarily comprising iron, steel, concrete and similar harmless materials, for which the concern is physical impact, and limited to those circumstances where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other than dumping.

Geographical coverage is wider, as it also governs storage of wastes in the seabed, as well as the abandonment, or toppling, of offshore installations (Article 1).

Although the internal waters of a State are excluded from the dumping provisions under both the Convention and Protocol, Parties to the Protocol have the option to apply its rules to their internal waters if they wish (Article 7).

The Protocol contains better linkages with other international environmental agreements (Basel Convention).

Storage of CO₂ under the seabed will be allowed from 10 February 2007, under amendments to an international convention governing the dumping of wastes at sea.

For Contracting Parties to the London Protocol of which the UK is one, recent amendments regulate the sequestration of CO₂ streams from CO₂ capture processes in sub-seabed geological formations. This means that a basis has been created in international

environmental law to regulate carbon capture and storage (CCS) in sub-seabed geological formations, for permanent isolation, as part of a suite of measures to tackle the challenge of climate change and ocean acidification, including, first and foremost, the need to further develop low carbon forms of energy. In practice, this option would apply to large point sources of CO₂ emissions, including power plants, steel and cement works.

The amendments (entered into force on 10 February 2007) state that CO₂ streams may only be considered for dumping, if: disposal is into a sub-seabed geological formation; they consist overwhelmingly of CO₂ (they may contain incidental associated substances derived from the source material and the capture and sequestration processes used); and no wastes or other matter are added for the purpose of disposing of them.

In conclusion, liability lies with the storage site operator (and also transport operator if at sea) under the precautionary principle. If storage takes place within internal waters only (which is unlikely in a UK context) then the London Dumping Convention does not need to apply.

3.4.5.3 OSPAR Convention

The operative provisions of the OSPAR Convention in respect of CCS activities are as follows.

Article 2 of the Convention states that Contracting Parties shall take all possible steps to eliminate pollution and protect maritime area as well as safeguard human health. It further states that, the precautionary principle shall be applied – preventative measures taken when reasonable grounds of concern exist that substances or energy introduced, directly or indirectly, into the marine environment may bring about hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea, even when there is no conclusive evidence of a causal relationship between the inputs and the effects. Polluter pays principle, by virtue of which the costs of pollution prevention, control and reduction measures are to be borne by the polluter (OSPAR Commission, 1992).

Article 21 of the OSPAR Convention is with regards to the Transboundary Pollution matter and it states that when pollution originating from a Contracting Party is likely to prejudice the

interests of one or more of the other Contracting Parties to the Convention, the Contracting Parties concerned shall enter into consultation, at the request of any one of them, with a view to negotiating a cooperation agreement (OSPAR Commission, 1992).

Annex I

Article 1 of the Annex I of the Convention states that when adopting programmes and measures for the purpose of this Annex, the Contracting Parties shall require, either individually or jointly, the use of best available techniques for point sources and best environmental practice for point and diffuse sources including, where appropriate, clean technology.

Furthermore, the Article states that the Contracting Parties have to take preventive measures in order to minimise the risk of pollution caused by accidents. In addition, the Article also requires that the Contracting Parties take into account of the following when adopting programmes and measures in relation to radioactive substances (including waste):

- The recommendations of the other appropriate international organisations and agencies;
- The monitoring procedures recommended by these international organisations and agencies

Annex II

Article 3 of the Annex II states that the dumping of all wastes or other matter is prohibited, except for listed in paragraphs 2 and 3 of this Article (OSPAR Commission, 1992). The list referred to in paragraph 1 of this Article is as follows:

- dredged material;
- inert materials of natural origin, that is solid, chemically unprocessed geological material the chemical constituents of which are unlikely to be released into the marine environment;

- sewage sludge until 31st December 1998;
- fish waste from industrial fish processing operations;
- vessels or aircraft until, at the latest, 31st December 2004;
- CO₂ streams from CO₂ capture processes for storage provided that disposal is into a sub-soil geological formation; the streams consist overwhelmingly of CO₂. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used; no wastes or other matter are added for the purpose of disposing of those wastes or other matter; they are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area (OSPAR Commission, 1992).

Annex III

Article 3 of Annex III prohibits any dumping of wastes or other matter from offshore installations. However, this does not include the discharge or emissions from offshore sources. Moreover, the prohibition referred to in paragraph 1 of Article 3 does not apply to CO₂ streams from CO₂ capture processes for storage provided that the following conditions are met³:

- Disposal is into a sub-soil geological formation;
- The streams consist overwhelmingly of CO₂ which may contain incidental associated substances derived from the source material and the capture, transport and storage processes used;
- No wastes or other matter are added for the purpose of disposing of those wastes or other matter;

³ This paragraph and the one which follows were introduced and adopted by amendments to the Annex agreed by OSPAR 2007

- They are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area (OSPAR Commission, 1992).

Article 4 of this Annex states that the Contracting Parties have to make sure no streams referred to in the list above is disposed of in sub-soil geological formations without authorisation or regulation by their competent authorities. It further states that such authorisation or regulation shall implement the relevant applicable decisions, recommendations and all other agreements adopted under the Convention (OSPAR Commission, 1992).

3.4.5.4 OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations

The purpose of the Decision is to seek the application of the OSPAR Guidelines for Risk Assessment and Management of Storage of CO₂ Streams in Geological Formations.

Accordingly, authorities shall ensure that CO₂ streams, which are stored in geological formations, are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area. This Decision shall be applied to any regulatory action, such as the granting of permits or approvals by the competent authorities concerning the storage of CO₂ streams in geological formations (OSPAR Commission, 2007).

Storage in geological formations of CO₂ streams from CO₂ capture processes shall not be permitted by Contracting Parties without authorisation or regulation by their competent authorities. Any authorisation or regulation shall be in accordance with the OSPAR Guidelines for Risk Assessment and Management of Storage of CO₂ Streams in Geological Formations, as updated from time to time. A decision to grant a permit or approval shall only be made if a full risk assessment and management process has been completed to the satisfaction of the competent authority and that the storage will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the

maritime area. The provisions of the permit or approval shall ensure the avoidance of significant adverse effects on the marine environment, bearing in mind that the ultimate objective is permanent containment of CO₂ streams in geological formations (OSPAR Commission, 2007).

Any permit or approval issued shall contain at least:

1. a description of the operation, including injection rates;
2. the planned types, amounts and sources of the CO₂ streams, including incidental associated substances, to be stored in the geological formation;
3. the location of the injection facility;
4. characteristics of the geological formations
5. the methods of transport of the CO₂ stream;
6. a risk management plan that includes:
 - monitoring and reporting requirements ;
 - mitigation and remediation options including the pre-closure phases; and
 - a requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options; monitoring shall continue until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level (OSPAR Commission, 2007).

The competent authorities shall require reports, including post-closure reports on the results of the risk assessment and management process from the operator. The data from these reports shall be made available to the Commission. Sufficient stakeholder involvement shall be ensured in the process of risk assessment and management as to ensure completeness in the assessment process.

This Decision entered into force, in respect of storage in accordance with Annex I to the Convention, on 15 January 2008 and, in respect of storage in accordance with Annexes II and III, from the date of entry into force of the amendments of those Annexes. Subsequent to the notification of a permit, the Contracting Party shall report to the next meeting of the appropriate OSPAR subsidiary body on the implementation of this Decision using, to the extent possible, the format as set out in Appendix Subsequent implementation reports shall be made annually.

In conclusion, regulation of CCS, especially in geological formations, is allowed under OSPAR and must follow national legislation, keeping in mind other international agreements. Perhaps there is room for an EU Directive to be superimposed over OSPAR without any contradiction as between the two regimes. The polluter pays and precautionary principles are to be observed in this regard. There are no specifics on liability of operators. Thus far, in a manner consistent with most international law, liability is placed on a national level (Contracting Party). Authorities must ensure that CO₂ streams, which are stored in geological formations, are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area. Any authorisation or regulation must be in accordance with the OSPAR Guidelines for Risk Assessment and Management of Storage of CO₂ Streams in Geological Formations and must follow its updates as well as report to the relevant OSPAR subsidiary bodies.

3.5 CCS in Other Jurisdictions and Lessons to be Learned

3.5.1 *Australia (Otway, Victoria State)*

CO₂CRC (The Cooperative Research Centre for Greenhouse Gas Technologies) has defined an operational Quality Health Safety and Environment Policy and has as a result developed a Management System. Insurance policies have been taken to ensure appropriate coverage for operational risks. The long term liability associated with the storage of CO₂ will be covered under the Research Development and Demonstration approval provision under the Victorian Environment Protection Act, recognising that more comprehensive legislative cover would be necessary in the future for any commercial geo-sequestration projects.

Onshore storage is to be legislated by the relevant state government, while federal legislation, consistent with the London Protocol, will cover offshore storage. However, the state governments have worked together to develop nationally consistent Australian Regulatory Guiding Principles. In addition to these guiding principles, applicable law concerning the position on liability comes in the form of the consultation upon and the results of the 2008 Offshore Petroleum Amendment (Greenhouse Gas Storage) Act. Consultations around the Act considered four possible positions on long term liability as follows: Government accepts all long term liability for CCS; Industry accepts all long term liability; Government and

industry share liability in some manner; or, the common law is the basis for liability. The 2008 legislation opts for the last option in which the common law is to be the basis for liability on the basis that it:

- Makes use of existing frameworks
- Provides incentive to industry to take practical actions to minimise exposure
- Provides a mechanism by which liabilities would be shared over time
- Does not set new precedents for government policy

It rejected other proposals owing to the fact that:

- They could impose higher costs than necessary on industry through the need to contribute to a fund which would be held in perpetuity;
- There was an issue as to determining the appropriate level of contribution to an industry fund;
- There was a lack of clarity on liability sharing between industry and government.

For the purposes of this research, a common law liability result is more manageable as it promotes the development of insurance products that can take their risk assessment and risk management cues from existing case law, while avoiding the uncertainties raised in this research in respect of emissions surrender allowances and the Environmental Liability Directive. Overall, the default common law liability position of the Australian Government would appear to be a favourable decision in respect of promoting innovation and investment in CCS.

3.5.2 Norway (*Sleipner*)

The Norwegian Sleipner project is an important precedent as the evidence base for CCS regulation in the UK is being built. This is the case for two reasons: thus far no significant leakage issues have arisen and the project has progressed as expected in this regard, secondly, the Sleipner project itself benefitted significantly from a carbon emission tax of €40 t/CO₂. As such, public sector participation in financing the project loomed large in incentivising CCS in this jurisdiction. Interestingly, the Sleipner project is silent as to the liability of the

Demonstration Project Operator, in effect absolving the project of any long term liability for leakage and transferring that responsibility to the government.

3.5.2.1 CCS under the Pollution Control Act

The Pollution Control Act regulates emissions both at land and at sea within the economic zone. A company whose undertakings will result in large emissions must obtain an emissions permit pursuant to the Pollution Control Act and fulfil the formal terms of that permit. The Norwegian Pollution Control Authority may set conditions to reduce or prevent emissions. For example, a condition in the permit for the new gas-fired power plant at Mongstad is that CCS technology be incorporated from the year 2014.

An emissions permit does not include the transport, deposition and storage of CO₂. This requires a specific permit. Because of the risks of leakage, the deposition and storage of CO₂ is considered pollution and requires a permit under the Norwegian Pollution Control Act (Norwegian Government, 1983). The Sleipner project for demonstrating storage of CO₂ in geological offshore reservoirs was granted such a permit by the Norwegian Pollution Control Authority after it had received an account of the environmental aspects of the project.

3.5.2.2 CCS under the Petroleum Act

The Norwegian State is the owner of the deposits of oil in the Norwegian territorial seas and has exclusive rights over the administration of the natural resources. CCS as part of petroleum activities, whether for the purpose of EOR (Enhanced Oil Recovery) or permanent storage on the continental shelf, is regulated by a permit under the Petroleum Act (Norwegian Petroleum Directorate, 1996).

3.5.2.3 CCS under the Norwegian Greenhouse Gas Emission Trading Act

Industrial activities included in the Norwegian Greenhouse Gas Emission Trading Act have to submit quotas equivalent to their emissions.

CO₂ may leak during capture, transport or storage and at present, the responsibility for leakages is not satisfactorily regulated under Norwegian law. According to the Pollution Control Act, the owner of the CCS installation would primarily be responsible for leakages (Norwegian Government, 2004).

On the other hand, it seems the system found in the Emission Trading Act places the responsibility for the leakage upon those who are obliged to submit quotas for emissions installations that form part of the chain. The alternative is to include each link of the chain in the emission trading system. This would oblige the owner of, for example, the transportation pipes, to submit quotas for any leakages from the pipes.

3.5.3 Canada

The Alberta Provincial Government set up a CAD 2 billion (as of 2008) CCS fund. Alberta's government has estimated that CCS could contribute around 70% of the province's CO₂ mitigation efforts and intends to have 3-5 projects operational by 2015. The Weyburn project has been operating for 10 years and provides an excellent example of how projects can operate across borders and boundaries (the Weyburn operations cover both sides of the US-Canadian border) (ECOAL, 2010).

In Alberta, the CCS Act will amend the *Mines and Minerals Act* so that a closure certificate will be issued upon the completion of a CCS Project (Makuch et al., 2012). Thereafter, the Government of Alberta will take on liability for the captured CO₂, assuming all obligations of the party that injected it into the ground (the lessee) including:

- Obligations as an owner and licensee under the *Oil and Gas Conservation Act* of the wells and facilities covered by the agreement that authorized the injection of the CO₂;
- Obligations as the person responsible for the injected captured CO₂ under the *Environmental Protection and Enhancement Act*;
- Obligations as the operator under Part 6 of the *Environmental Protection and Enhancement Act* in respect of the land within the location of the agreement used by the lessee in relation to the injection of CO₂; and
- Obligations under the *Surface Rights Act*.

A closure certificate will be accompanied by a release of the lessee by the Government. The Government will also indemnify the lessee against liability for damages in an action in tort if liability arises in relation to an action or omission of the lessee occurring in the context of the initial permitted injection of CO₂.

In short, the issuance of a closure certificate results in the full-scale, permanent assumption by Alberta of all liabilities that may arise in relation to the injected CO₂ (Averbach et al., 2010).

3.5.4 *United States of America*

CCS-specific legislation is being developed on a state-by-state basis. There are several regional sequestration projects which highlight US action and co-operation on CCS at local level. In respect of CO₂ injection, for maximized hydrocarbon extraction there is a 20 year history of environmental permitting experience. In North Dakota for example, *all liability passes from the operator to the state within 10 years of the closure of a project* (Javedan, no date).

As the US Department of Interior has recently been criticised for its lax approach to issuing permits for oil and gas drilling, it has been mandated that the competent authority to deal with these issues will be the Bureau of Ocean Energy Management. This authority is expected to draft comprehensive permit regulations for offshore oil and gas in the very near future. As for the matter of CCS, there exists a *Class V Experimental Technology Well Guidance for Pilot Geologic Sequestration Projects* drafted by the US Environmental Protection Agency (EPA). This document establishes some of the regulatory measures proposed for the implementation of CCS technology.

The finalised requirements for CCS under the authority of the EPA include the development of a new class of storage wells (Class VI) to be used specifically for geological storage of CO₂. The regulations for Class VI wells and CCS activities in general come under the authority of the Safe Drinking Water Act's (SDWA) Underground Injection Control (UIC) Program. Also known as the Class VI rule, these requirements are designed to protect underground sources of drinking water. They address CO₂ injection for long-term storage and

ensure that wells used for CO₂ are appropriately sited, constructed, tested, monitored, funded and closed. Furthermore, the rule gives operators injection depth flexibility in various geological settings in which geologic sequestration may occur, including very deep formations and oil and gas fields that are transitioned for use as CO₂ storage sites.

It is of note that there is also a complimentary EPA ruling under the authority of the Clean Air Act. The US EPA has finalized reporting requirements under the Greenhouse Gas Reporting Program for facilities that inject CO₂ underground for geological sequestration and all other facilities that inject CO₂ underground. Thus, information obtained under the Greenhouse Gas Reporting Program will enable EPA to track the amount of CO₂ received by these facilities. Detailed regulations for that legislation are forthcoming.

Perhaps the most relevant document when looking at the way that the USA addresses CCS long-term liability for storage is the *Underground Injection Control (UIC), Class VI Program Research and Analysis in Support of UIC Class VI Program, Financial Responsibility Requirements and Guidance*. This document was signed and issued in late November 2010 and contains relevant information regarding the future permitting of CCS on a Federal Level as well as stakeholder consultation feedback which was used by the EPA in drafting the guidance document. Especially important is the section which addresses Post-Injection Site Care (PISC) discussed below.

PISC is the period after injection ceases but before site closure, during which the operator must continue monitoring to ensure US Drinking Water (USDW) protection from endangerment. Moreover, having a PISC monitoring plan is singled out as an important part of the CCS permitting process. The EPA has proposed that during PISC, owners or operators of Class VI wells would be required to periodically monitor the site and track the position of the CO₂ plume and pressure front to ensure USDWs are not endangered. The proposed default PISC timeframe is 50 years after injection had been terminated. This timeframe was based on a review of research studies, industry reports and existing environmental programs. In order to support site-specific flexibility, the proposed rule stipulated that the PISC timeframe could be shortened by the Director after cessation of injection if the owner or operator is able to demonstrate that USDWs would not be endangered prior to 50 years. Similarly, if after 50 years the Director determined that USDWs may still become endangered by the CO₂ plume and/or pressure front, they could lengthen the PISC timeframe.

Industrial stakeholders have since been consulted and have expressed a wish to reduce that timeframe citing significant, even prohibitive operative costs for such extensive periods. On the one hand, it was suggested by some that the PISC timeframe should be specific to the characteristics of a project including the predicted extent of the CO₂ plume and the area of elevated pressure, geological factors, modelled predictions of CO₂ trapping and subsurface geochemical reactions. In addition, they suggested that the PISC period be established in a case by case basis as part of the permitting process. On the other hand, others supported the 50 years timeframe indicating that the risks of CCS are still unclear and thereby a conservative monitoring time is a good idea. Yet another group of stakeholders have proposed a combination of fixed time and performance standards as good balance between the two suggested options and as the preferable approach.

The EPA acknowledges the merits of a performance-based approach for the PISC timeframe, especially recognizing the variety of site conditions that will affect the appropriate PISC timeframe, and therefore EPA officials have decided that the EPA Director will be in the best position to make a site-specific determination allowing for the PISC timeframe to be modified while ensuring USDWs are not endangered. Therefore, the EPA retains the proposed default 50-year PISC timeframe with additional flexibility allowed by discretion of the Director. This allows the Director discretion to shorten or lengthen the PISC timeframe during the PISC period based on site-specific data as well as affords them the discretion to approve a Class VI well owner or operator to demonstrate, based on substantial data gathered during the permitting process, that an alternative PISC timeframe is appropriate if it ensures non-endangerment of USDWs.

With regards to site closure, the EPA has proposed that if a site is determined to no longer pose a risk of endangerment to USDW, the Director would be able to approve site closure and the operator would be required to properly close site operations. The closure activities are similar to those for other well classes and include plugging all monitoring wells, submitting a site closure report and recording a notation on the deed to the facility property or other documents that the land has been used to inject and store CO₂. Operators are obligated by their permits to demonstrate and maintain financial responsibility for performing corrective action on wells in the area of review, injection well plugging, PISC and site closure and emergency and remedial response. These financial responsibility requirements ensure that owners or operators have the resources to carry out activities related to closing and

remediating GS sites if need be during injection or after wells are plugged but before site closure is approved so that they do not endanger USDWs.

The proposed EPA approach to financial responsibility regulations follows previous systems for financial assurance of other classes of wells. This is typically performed through two broad categories of financial instruments:

- Third party instruments: including surety bonds, financial guarantee bond or performance bond, letters of credit and an irrevocable trust fund
- Self-insurance instruments: including corporate financial test and corporate guarantees

Currently, the EPA believes that there is a need to adjust these instruments for CCS. However, it has indicated that such instruments can be supplemented by additional financial responsibility instruments. In addition, the EPA has chosen to allow for separate financial demonstration for injection well plugging and PISC (i.e. a demonstration which will be submitted prior to well plugging and the beginning of the post-injection site care period rather than with the permit application) (D. Edwin Hogle and Sharon L. Kercher, no date).

Stakeholder consultations performed by the EPA have discussed the relative strengths and weaknesses of various financial responsibility instruments and expressed a specific concern for the risk of bank failures and corporate insolvency which has potential to leave financial obligations unfunded. Generally speaking, stakeholders are in agreement with the EPA in supporting the provision of separate financial instruments for injection well plugging and PISC. There has been, however, concern about potentially high costs and long time frames of CCS with some stakeholders believing that financial assurances would be difficult to obtain, particularly though the duration of PISC and may discourage investment. Furthermore, stakeholders also expressed the need for regulatory certainty to help inform financial requirements for well owners and operators. The EPA was proposed to be the competent authority which specifies the acceptability of various financial responsibility instruments, specifically acting to inform State legislatures with information on what instruments they should approve in order to meet Federal requirements.

Despite the general approval for additional financial responsibility instruments to supplement those established by previous regulations, it has been suggested that the proposed framework

leaves too much discretion to the EPA Director which may leave operators with a heightened risk of having their financial instrument of choice rejected. In order for operators to operate with flexibility in their choice of instrument, it has been proposed that the Director would be allowed discretion of choice in assessing these instruments, but would have to do so in the context of operational and site-specific factors, including the assessment of project risk over time. This conditional approach is a sensible proposal.

The Environmental Financial Advisory Board (EFAB) agreed that both self-insurance and third-party insurance should be made available to responsible parties. They have also supported the requirement that third-party providers, such as insurers, pass financial strength requirements, such as the use of credit ratings, to demonstrate financial strength, stipulating that the owner or operator should notify the Director in the event of bankruptcy. The EFAB also agreed that financial responsibility requirements ought to be linked to cost estimates, with regular updates to both cost estimates and financial responsibility demonstrations. Additionally, the EFAB specifically recommended (Environmental Financial Advisory Board (EFAB)):

- The use of standardised language for financial instruments. (Although EFAB did not recommend the use of standardized policy language for insurance, they did suggest that procedures be adopted so that the Director can specifically agree to limitations contained in the insurance policy or specifically reject such limitations during the review process).
- That the owner or operator be required to notify the Director by certified mail of any proceeding under bankruptcy within 10 business days after the commencement of the proceeding.
- That owners or operators be deemed to not possess the required financial responsibility in the event of bankruptcy, insolvency, or a suspension or revocation of the license or charter of the third party when using letters of credit, surety bonds, or insurance policies or loss of authority of the third party to act as a trustee when using a trust fund.
- That because the RCRA financial mechanisms, which are largely used in the SDWA Class I program, were developed based on hazardous waste facility owner's or operator's considerations, there may be differences in the owner or operator profiles for proposed Geological Storage facilities that warrant additional assurance

mechanisms. Thus, the Agency should consider adding a new category of financial assurance to the Class VI program that provides the Agency with the flexibility to approve the "functional equivalent" to the established RCRA financial assurance tests.

- That the EPA considers the use of rate-based financing, a new category of instrument that would provide the Director with the flexibility to approve instruments that are functionally equivalent to existing qualifying instruments.

Having consulted stakeholders and the EFAB, the EPA has announced its decision for final regulation to retain the substantive requirements that owners or operators of class VI wells must demonstrate and maintain financial responsibility to cover cost of corrective action, injection well plugging, PISC and site closure and emergency and remedial response. The EPA also proposed that this regulation be modified in order to provide clarity on acceptable instruments and to enhance the enforceability of such financial requirements as well as set reporting timeframes to provide consistency with other EPA regulations. Specifically, the EPA has clarified the financial responsibility requirements by:

- Describing "qualifying instruments" to cover the cost of corrective action, injection well plugging, PISC and site closure, and emergency and remedial response in a manner that prevents endangerment of USDWs.
- Adding language clarifying that the financial responsibility instrument is directly enforceable regardless of whether the requirement is a condition of the permit.
- Requiring submission of annual inflationary updates and specifying a 60-day timeframe after notification by the Director for the submission of written updates of adjustments to the cost estimate.
- Requiring owners or operators to notify the Director no later than 10 days after filing for bankruptcy.
- Requiring an owner or operator or its guarantor using self-insurance to demonstrate financial responsibility for GS to meet a Tangible Net Worth of an amount approved by the Director; have both a net working capital and a tangible net worth of at least six times the sum of the current well plugging, post-injection site care and site closure cost; have assets located in the US amounting to at least 90 percent of total assets or at least six times the sum of the current well plugging, post-injection site care and site closure cost; submit annual report of bond rating and financial information; and either

- 1) Pass a bond rating test issued by one or both of the nationally recognized bond rating agencies, Standard & Poor's and Moody's for which the bond's rating must be one of the four highest categories (i.e., AAA, AA, A, or BBB for Standard & Poor's or AAA, AA, A, or Baa for Moody's)); or,
- 2) Meet all of the following five financial ratio thresholds:
 - A ratio of total liabilities to net worth less than 2.0
 - A ratio of current assets to current liabilities greater than 1.5
 - A ratio of the sum of net income plus depreciation, depletion, and amortization to total liabilities greater than 0.1;
 - A ratio of current assets minus current liabilities to total assets greater than -0.1;
 - A net profit (revenues minus expenses) greater than 0.

These requirements are not meant to duplicate existing financial responsibility regulations but are instead tailored to the unique characteristics and requirements of CCS. Considering the potential high costs associated with large scale CCS deployment, the EPA wishes to ensure appropriate and continuous financial mechanisms are in place throughout the lifetime of a project and that costs associated with CCS operation are not passed along to public. The EPA thus supports stringent self-insurance instruments in addition to annual evaluations of financial instruments minimizing the potential for institutions that have passed the financial test to then suffer financial difficulties which would hinder the financial demonstration of CCS projects.

The EPA does not have authority under SDWA to be the direct or indirect beneficiary of a trust fund under this statute for the purpose of establishing financial responsibility for CCS projects. The EPA must comply with the Miscellaneous Receipts Act and therefore standby trust funds are not allowed to be the sole financial instruments that can be used by an owner or operator to demonstrate financial responsibility. Standby trusts must be used in conjunction with certain types of financial responsibility instruments (e.g., surety bonds, letters of credit or escrow accounts) in order to enable the EPA to be party to the financial responsibility agreement. The final EPA ruling identifies the following qualifying financial instruments for Class VI wells, all of which must be sufficient to address endangerment of USDWs. Moreover, standby trusts are not needed for options 1, 4, and 5.

- 1) Trust Funds: If using a trust fund, owners or operators are required to set aside funds with a third party trustee sufficient to cover estimated costs. During the financial responsibility demonstration, the owner or operator may be required to deposit the required amount of money into the trust prior to the start of injection or during the "pay- in period" if authorized by the Director.
- 2) Surety Bond: Owners or operators may use a payment surety bond or a performance surety bond to guarantee that financial responsibility will be fulfilled. In case of operator default, a payment surety bond funds a standby trust fund in the amount equal to the face value of the bond and sufficient to cover estimated costs, and a performance surety bond guarantees performance of the specific activity or payment of an amount equivalent to the estimated costs into a standby trust fund.
- 3) Letter of Credit: A letter of credit is a credit document, issued by a financial institution, guaranteeing that a specific amount of money will be available to a designated party under certain conditions. In case of operator default, letters of credit fund standby trust funds in an amount sufficient to cover estimated costs.
- 4) Insurance: The owner or operator may obtain an insurance policy to cover the estimated costs of GS activities requiring financial responsibility. This insurance policy must be obtained from a third party to decrease the possibility of failure (i.e., non-captive insurer).
- 5) Self-Insurance (i.e., Financial Test and Corporate Guarantee): Owners or operators may self-insure through a financial test provided certain conditions are met. The owner or operator needs to pass a financial test to demonstrate profitability, with a margin sufficient to cover contingencies and unknown obligations, and stability. If the owner or operator meets corporate financial test criteria, this is an indication that the owner or operator can guarantee its ability to satisfy financial obligations based solely on the strength of the company's financial condition. An owner or operator who is not able to meet corporate financial test criteria may arrange a corporate guarantee by demonstrating that its corporate parent meets the financial test requirements on its behalf. The parent's demonstration that it meets the financial test requirement is insufficient if it has not also guaranteed to fulfil the obligations for the owner or operator.
- 6) Escrow Account: Owners or operators may deposit money to an escrow account to cover financial responsibility requirements. This account must segregate funds

sufficient to cover estimated costs for GS financial responsibility from other accounts and uses.

- 7) Other instrument(s) satisfactory to the Director: In addition to these instruments, EPA anticipates that new instruments that may be tailored to meet GS needs may emerge, and may be determined appropriate for use by the Director for the purpose of financial responsibility demonstrations.

The final rule specifies that the qualifying financial responsibility instrument must include protective conditions of coverage, including, but not limited to: cancellation, renewal and continuation provisions; specifications on when the provider becomes liable in case of cancellation if there is a failure to renew with a new qualifying financial instrument; and requirements for the provider to meet a minimum credit rating, minimum capitalization, and ability to pass the bond rating when applicable. This clarification was made in direct response to issues raised by commenter's for numerous instruments and also to make sure that there is no gap in coverage should a financial instrument fails. Furthermore, it requires the owner or operator to have a detailed written estimate, in current US dollars, of the cost of: performing corrective action on wells in the area of review, plugging the injection well(s), PISC and site closure and emergency and remedial response. A cost estimate must be prepared separately for each of these activities and be based on the costs to the owner or operator of hiring a third party (who is neither a parent nor a subsidiary of the owner or operator) to perform the activities. The EPA will not allow for a separate financial responsibility demonstration for well plugging and PISC (i.e., a demonstration submitted prior to well plugging and the beginning of the PISC period rather than with the permit application). A demonstration of financial responsibility for all phases of the GS project will be required prior to the issuance of a Class VI permit, however, an owner or operator may demonstrate financial responsibility by using one or multiple qualifying financial instruments for specific GS activities, thereby realizing greater flexibility and cost savings from this regulation.

It must be noted also that the EPA has added language that a financial responsibility instrument is directly enforceable regardless of whether the requirement is a condition of the permit or not. It also specifies circumstances under which an owner or operator may be released from a financial instrument, including that the owner or operator has completed the geological storage project activity for which the financial instrument was required and has fulfilled all financial obligations as determined by the Director, or has submitted a

replacement financial instrument and received written approval from the Director accepting the new financial instrument and releasing the owner or operator from the previous financial instrument. The Director's determination of completion of a geological storage project activity may be sustained by a professional engineer's report on completion as well as by guidance (currently being developed), which will provide direction to the Director for when a demonstration may no longer be adequate to cover the GS activities.

As a Federal agency, the EPA's remit is to create a nationally consistent financial responsibility program for CCS activities, however it does, simultaneously provide State permitting authorities with an appropriate level of flexibility. The EPA is in the process of developing guidance on financial responsibilities for owners or operators of Class VI in order to assist said stakeholders in evaluating the financial responsibility requirements for Class VI wells and to assist Directors in evaluating financial responsibility demonstrations. Additionally, under SDWA authority, owners or operators of injection wells must ensure the protection of underground sources of drinking water from endangerment and are subject to liability for enforcement under the USDW Act.

Once an owner or operator has met all regulatory requirements under Part 146 for Class VI wells and the Director has approved the site, the owner or operator will generally no longer be subject to enforcement under section 1423 of SDWA for noncompliance with UIC regulatory requirements. However, an owner or operator may be held liable for regulatory noncompliance under certain circumstances even after site closure is approved such in cases where the owner or operator provided erroneous data to support an approval of site closure. In addition, an owner or operator may always be subject to an order should the Administrator deem necessary to protect the health of persons under section 1431 of the SDWA after site closure if there is fluid migration that causes or threatens imminent and substantial endangerment to a USDW. For example, the Administrator may issue a SDWA section 1431 order if a well may present an imminent and substantial endangerment to the health of persons, and the State and local authorities have not acted to protect the health of such persons. The order may include commencing a civil action for appropriate relief. If the owner or operator fails to comply with the order, they may be subject to a civil penalty for each day in which such violation occur or failure to comply continues. Furthermore, after site closure, an owner or operator may, depending on the fact scenario, remain liable under tort and other remedies, or under other Statutes including, but not limited to, Clean Air Act.

Under current SDWA provisions, the EPA does not have authority to transfer liability from one entity (i.e., owner or operator) to another.

3.6 Assessment of Risks from Similar Industries

This section of the thesis examines three mature regulatory and financial regimes that may inform the manner in which liability should be managed in a CCS context. They include oil and gas facility permitting, the management of oil spills at sea, the nuclear industry and landfill site regulation.

3.6.1 *Oil and Gas Industries*

What is being covered in this section is comparable to Carbon Capture and Storage's financial and regulatory aspects in the sense that in both cases an international pool fund may be appropriate in case of incidents such as leakage or structural failure of the vessels (Makuch et al., 2011).

Accordingly, funds could be drawn down to cover the cost of damages. The consequences of the failure of both cases i.e. Oil and Gas spills and CCS are broadly similar. When such vessels fail or leak, oil and gas gets released into either the atmosphere or water. Similarly, failure of CCS projects has the same consequences. If there is a leak in deep geological formations, the captured CO₂ can potentially be released into the atmosphere and in case there is a leak in the ocean, the captured CO₂ can potentially be released into the water making the water acidic and subsequently harming marine life.

During transportation of gas or oil, care must be observed to ensure that it is not spilt or no leakage occurs as this poses a threat to the human health and safety and that of the environment.

To deal with the risks involved in this industry, several types of insurance regimes have been developed. Vehicles transporting oil or gas are insured against potential risks of fire in addition to other risks that may be faced with during transportation of these sources of energy

(Broderick et al., 2000). In case hazards results during production of gas, litigation on who pays for the losses suffered makes an assessment on whether the contamination could have been avoided or it was accidental (Tjernshaugen, 2008). The amounts paid in insurance vary across the nations given the legal and institutional frameworks guiding the process (Pritchard, 2005).

- Jurisdiction

The Convention (1992 Conventions on Liability and Compensation for Oil Pollution Damage) applies.

a) To pollution damage caused:

- In the territory, including the territorial sea, of a Contracting State
- In the exclusive economic zone of a Contracting State, establishment in accordance with international law, or, if a Contracting State has not established such a zone, in an area beyond and adjacent to the territorial sea of that State in accordance with international law and extending not more than 200 nautical miles from the baselines from which the breadth of its territorial sea is measured

b) To preventive measures, whenever taken, to prevent or minimize such damages.

- Regime Type

The international financial fund mentioned holds the funds contributed by each member states in each calendar year. The way in which this contribution amount is calculated has been explained in the “Amount” sub-section (pertaining to the fund pool).

- Risk Type

The possible risks associated with oil and gas rigs are mainly owed to adverse weather conditions such as super storms, hurricanes, earthquakes and other violent sea conditions, different modes of structural failures of the vessels which could result in the complete collapse of the rig and human error and/or negligence which could cause different problems such as fire and subsequently leakage of both oil and gas.

Furthermore, oil and gas could escape to drains, and into houses, or escape into cities with varying consequences for people and the environment.

- Risk Longevity

The type of risks mentioned can exist for as long as oil is being drilled, recovered and shipped. Furthermore, the risks can also exist when the recovery of oil is finished and the wells are closed due to aging of the well plug.

- Who Pays

An International Fund for Compensation for pollution damage named “The International Oil Pollution Compensation Fund 1992” pays the costs of the damages resulted from an accident providing that the Fund cannot prove that the accident was intentional or as a result of negligence and misconduct.

According to Article 10, paragraph 1 (a) and (b) of the Convention, annual contributions to the fund are to be made in respect of each Contracting State by any person who in the calendar year has received in total quantities exceeding 150,000 tones.

- Amount

In order to assess the amount of annual contributions of each member state, if any, and taking account of the fact that there needs to be sufficient liquid funds available, the Assembly makes an estimate in the form of a budget of Expenditure and Income for each calendar year:

The Assembly decides the total amount of contribution needed to be levied from the Contracting States. On the basis of that decision, the Director, calculates the amount annual contribution for each person referred to in Article 10 of this Convention.

The maximum amount of compensation payable by the Fund is 200 million units of account with respect to any incident occurring during any period when there are three Parties to this Convention in respect of which the combined relevant quantity of contributing oil received by persons in the territories of such Parties, during the preceding calendar year, equalled or exceeded 600 million tons.

“The units of account” is the special Drawing Right as defined by the International Monetary Fund (IMF). The amounts mentioned will need to be converted into national currency.

A tanker owner's liability limit under the Civil Liability Convention depends on the size of the tanker. The liability limits set out in the Civil Liability Convention in respect of claims following a spill of persistent oil are as follows:

- For all tankers with a gross tonnage up to 5,000: 4.51 million Special Drawing Rights (SDR);
- For tankers with a gross tonnage of between 5,000 and 140,000: 4.51 million SDR plus 631 SDR for each gross ton in excess of 5,000; and
- For tankers with a gross tonnage of 140,000 and over: 89.77 million SDR.

- Risk Measure Effectiveness

Noting that there have been no defaults on fund pay-outs to date, there is little financial risk with this instrument. On a practical note, if the best available technologies are applied to minimise the risks such as structural failure of different members within the structure of the vessel, then the main risks will be owing to severe weather conditions and human error and negligence.

Furthermore, vessels leak oil when they are not designed to a high standard that meets international requirements (double hull instead of single hull). Therefore, the design method also needs to be considered too as one of the most important factors in the stability of the vessels.

3.6.2 Nuclear Power Plants

The main safety issues that nuclear power stations may face include:

- Waste Management: In relation to radioactive material storage and disposal, one has to ensure that the right technical standards are put in place in order to protect public safety and the environment.

- Leak of Radiation: In relation to plant level operations, one has to constantly implement preventive measures in order to protect people and the environment from harmful effects of ionising radiation on and off site.

The risk longevity for radioactive waste is significant. High-level radioactive waste is generally material from the core of the nuclear reactor or nuclear weapons. Most of the radioactive isotopes in high level waste emit large amounts of radiation and have extremely long half-lives (some longer than 100,000 years) creating long time periods before the waste will settle to safe levels of radioactivity. Therefore, the potential risks can last for 100,000 years. The potential risks of nuclear facilities and CCS are similar in terms of the possibility of leakage (Makuch et al., 2011). Although, clearly radioactive leakage contamination is more dangerous than CO₂ leakage and as such potential environmental damage for radioactive leakage is much higher.

Support from nuclear power plants from the public declined following the Fukushima and Nagasaki crisis. The risks experienced in this industry emanate from issues of storage of wastes from nuclear power plants, leakage at the industries' sites and earthquakes (Smith and Maremont, 2011). This leakage could lead to devastating impacts to the human health and the environment. Furthermore, these emissions may be taken up by plants and bio accumulate in living organisms thereby the impacts of any leakage would continue being experienced long after an accidents. Moreover, leakage could also result from accidents in the industry.

3.6.2.1 The UK Nuclear Installations Act (1965)

In the UK, we find one of the toughest and most thorough regulatory frameworks for the nuclear sector in the world. Nuclear liabilities are covered by the Nuclear Installations Act 1965 as amended. The licensee is required to provide cover for third party claims within the limits prescribed by the Act in accordance with arrangements approved by the Health and Safety Executive (or the Scottish Executive for Scotland). The Health and Safety Executive (or the Scottish Executive) will review the adequacy of the licensee's section 19 cover, which may be provided by insurance, indemnity or other approved means. This will usually be done when a new site is licensed, when there is a new licensee, or when there is a change to the insurance status of the site.

In the UK, the Energy Act 1983 brought legislation into line with earlier revisions to the Paris/Brussels Conventions and set a new limit of liability for particular installations. After that, in 1994 this limit was increased to £140 million for each major installation. Therefore, the operator is liable for claims up to this amount and must insure accordingly.

- Who Pays

The majority of this insurance is provided by a pool of UK insurers comprising 8 insurance companies and 16 Lloyds syndicates (Nuclear Risk Insurers Limited (NRI)).

- Amount

Beyond £140 million, the current Paris/Brussels system applies, with government contribution to €360 million. The Government was planning legislation for 2010 which would require insurance above the £140 million level, and towards the €700 million level specified under the 2004 Paris/Brussels Protocol (when it enters force), this to be provided by government at commercial rates.

The most recent site management contract, signed in 2008 for Sellafield lasts for 17 years and expects the operator (Areva) to insure itself against the first £140m of an accident, the balance being covered by the Government.

- Risk Measure Effectiveness

The risk of waste mismanagement is minimal and so is the risk of leakage. The only other possible major risk is the risk of the core being melted. This has not occurred since the partial core meltdown of the Three Mile Island Nuclear Generation Station 1979. Nowadays, the nuclear industry believes that the power stations are 100% safe. However, there is always a possibility of radiation leakage and problems arising with mismanagement of the nuclear waste based upon human error.

- Liquidity

The funds will be available by the insurance companies that will insure the power station in case an accident or disaster occurs. According to the World Nuclear Association, operators of nuclear power plants are liable for any damage caused by them, regardless of fault.

- Duration

The instrument will remain active for as long as the power station is not decommissioned and is still working and generating electricity. In relation to flexibility, the instrument may be amended by the Government or the insurance companies if need be.

3.6.2.2 The US Price-Anderson Act (1957)

The Price-Anderson Nuclear Industries Indemnity Act is a United States federal law, first passed in 1957 and since renewed several times, which governs liability-related issues for all civil nuclear facilities constructed in the United States before 2026. The main purpose of the Act is to partially indemnify the nuclear industry against liability claims arising from nuclear incidents while still ensuring compensation coverage for the general public. The Act establishes a no fault insurance-type system in which the first approximately \$12.6 billion (as of 2011) is industry-funded as described in the Act (any claims above \$12.6 billion would be covered by the federal government) (USNRC, 2011).

Power reactor licensees are required by the act to obtain the maximum amount of insurance against nuclear related incidents which is available in the insurance market (as of 2011, \$375 million per plant) (USNRC, 2011). Any monetary claims that fall within this maximum amount are paid by the insurer(s). The Price-Anderson fund, which is financed by the reactor companies themselves, is then used to make up the difference. Each reactor company is obliged to contribute up to \$111.9 million in the event of an accident. As of 2008, the maximum amount of the fund is approximately \$11.6 billion if all of the reactor companies were required to pay their full obligation to the fund (USNRC, 2011). This fund is not paid into unless an accident occurs. However, fund administrators are required to have contingency plans in place to raise funds using loans to the fund, so that claimants may be paid as soon as possible. Actual payments by companies in the event of an accident are capped at \$17.5 million per year until either a claim has been met, or their maximum individual liability (the \$111.9 million maximum) has been reached.

Over the first 43 years of the Price-Anderson Act to 2000, secondary insurance claims did not arise. A total of \$151 million was paid to cover claims (including legal expenses), all from

primary insurance, including \$70 million for Three Mile Island. Additionally, the Department of Energy paid about \$65 million to cover claims under liability for its own nuclear operations in the same period.

3.6.3 *Waste Management Sites – Landfill*

Landfill sites represent a potentially useful comparison with CCS storage sites on the basis that both facilities entail risk of leakage during the site life and well beyond it. Both sites feature risks that arise beneath the earth's surface (and as such are conventionally out of view) and both risks may be large.

In legal terms, there are also similarities in that regulatory authorities use a permit mechanism as the primary regulator of standards and liability issues are addressed through this mechanism. The two sites are dissimilar in that landfill sites are at their greatest service to the public interest during the life of the site (i.e. before site closure) whereas CCS storage sites serve the public interest during the entire life of the sight, at least because the storage of the greenhouse gas emissions prevents their release into the environment on a permanent basis. For private firms in the waste management business, there is also the comparative advantage of decades of experience in site management and the uses of well-established technologies for landfill management. By contrast, CCS storage site investors and operators are required to shoulder the operational and long term risks of an emerging technology which the Government has accepted as a key component of greenhouse gas emissions abatement strategy for long term compliance with national, European Union and international laws and imperatives. Noting the public and environmental interest functions served by CCS and the large range of risk evaluation and decision-making powers available to regulators, there is an issue as to the fairness of placing essentially all of the risk on storage site operators rather than sharing that risk with Government and/or putting appropriate risk mitigation instruments in place at a regulatory level.

- Jurisdiction

The first contemporary waste legislation in the UK came by way of the Environmental Protection Act 1990 as subsequently amended by the Environment Act, 1995.

In the UK, the EU Landfill Directive 1999/31/EC was transposed into UK law in 2002. The Environmental Permitting Regulations, 2010, SI 675 and SI 676 now supplement the said Directive.

- Objective

The objective of this legislation is to reduce the dependence on landfill sites, which are rapidly filling up, and will be full soon, and to reduce the emissions of greenhouse gases such as methane and CO₂, which cause global warming and damage the upper atmosphere by destroying the ozone layer. Furthermore, certain metals are becoming scarce and recycling will reduce the need to make new quarries and mines. The legislation also seeks to improve public health, protect water supplies and aquifers. It is aimed at stopping run-off (leachate) from waste getting into water supplies (and reducing rodent and vermin populations).

- Régime Type

The regulatory regime in place is highly similar to that established by the CCS Directive with both focusing upon technical compliance through environmental permitting of facilities.

As a complement to the permitting regime for guarding against environmental damage, there is a Landfill Tax which encourages a reduction in the amount of waste created and disposed of in landfills. Imposed limits to national percentages of waste disposed of in this way. The risk of both EU (where the Environment Agency has not sufficiently well-enforced compliance with Waste Directives) and UK fines for non-compliance encourages appropriate regulatory compliance behaviour.

- Risk Types

There are factual and potential risks associated with landfill site operations. Factual risk appears as damage to the environment from uncontrolled waste disposal, such as vermin, water sources damage, fly tipping and chemical and oil damage to the land (future crops and ground use). Waste tips and landfill sites do give off methane, it can be seen burning and smelt, and this does damage the upper atmosphere.

Potential risk is the possibility of future damage of the kind mentioned above as well as chemical damage to the atmosphere that has not yet been proven. The flow of leachate into ground water supplies continues to be a large concern in the post-closure period.

- Risk Longevity

In sealed “tombs”, waste can decay for a minimum of 20-30 years resulting in methane (used or burnt off) and inert residue. In dry conditions the relevant waste will not decay as well, and thus the threat of damage can last longer. It is also possible that extraction equipment will decay and where site management seeks to reduce the period of decay and emissions, to reduce costs of equipment and loss of use of the land this can exacerbate the risks identified with landfill sites in their post-closure phases.

- Who Pays

In respect of three phases of investment in landfill sites (pre-operational, operational and closure), it is the site operator that has financial responsibility and therefore liability for the landfill site. Once the Environment Agency is satisfied that the site does not represent a hazard to the environment, then the operator's responsibilities in respect of maintenance, monitoring and control end. Insurance and longer term financial guarantees are the instruments that are generally in use to cover conventional environmental liabilities. This is to be contrasted with the absence of long term liability insurance mechanisms pertaining to CCS.

- Amount

According to industry insiders, the costs that arise in respect of planning and permitting consents before a landfill operation is opened for business are in the region of £2 million. Thus, landfill sites must have a minimum 1.5 million cubic meter minimum capacity if they are to be profitable at all. Profits on turnover for larger operations have been +/- 5% of annual turnover. These figures rest against the backdrop of the policy goal to raise landfill costs (in part by the Landfill Tax) with operators paying £48 tax per tonne (rising £8 per year to 2013 at least) as a means of encouraging alternatives pertaining to reduction, reuse, recycling and energy from waste. There is little evidence that financial guarantees have not been sufficient in respect of any post closure long-term liabilities for contemporary landfill circumstances.

According to the Right Honourable Caroline Jackson, the Member of the European Parliament that steered the EU Landfill Directive through the EU Parliament, Landfill charges internalise these financial guarantees so that they do not represent an added cost to waste management firms themselves.

- Risk Effectiveness

By containing waste in “tombs”, the liquid leachate and waste gases are controlled and contained. Once isolated, they can be dealt with and separated from human activity. However, further to the July/August Municipal Solid Waste Management Journal, the most common landfill management method still has its problems as follows:

The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and someone (normally the State Government) needs to be responsible for stepping in and taking corrective action when a problem is detected. Nevertheless, even in the United States which has a large history with landfills, federal legislative rules require only 30 years of post-closure monitoring by the landfill operator and do not require the operator to set aside funds for future corrective action.

- Certainty

The disposal of waste by landfill goes back to Roman times. It is an inexpensive form of waste disposal, but it has enduring environmental problems associated with it. Against the background of significant and demonstrable environmental effects with landfill sites including in their post-closure phases it is encouraging that most landfills are properly closed and de-commissioned before they come under a duty of care of the Government. In this context, it is appropriate that the financial guarantee – that is collected as part of landfill tipping fee rates – should cease to apply in connection with the site closure stage.

The nature of the financial guarantee is such that it is mandated and administered in the legal jurisdiction of the UK. No insolvency issues have arisen with the vast majority of firms that deliver landfill services, as there is a financial fitness test that applies to such firms.

Moreover, the financial guarantee is normally registered with and remains on deposit with the regulated, major chartered bank.

- Liquidity

As public taxes, industrial charges and guarantees apply to landfills in the form of obligations to the Government that must be fulfilled as a condition of permit compliance (i.e., the right to operate a business which involved significant front end expenditure and hence a desire to recover upon said investment), there is no obvious risk of default. Moreover, even if a site were orphaned, in theory landfill tax revenues could be diverted to remediation objectives if there were the regulatory need to do so. As remediation orders can be granted without trial, the legal process for obtaining compensation by way of financial guarantee is as straightforward as obtaining an order from a judge in chambers. For emergency remediation activities, this can occur on the same day as the order is filed.

- Flexibility

The law applies to all disposals at landfill sites, so it is not flexible in respect of compliance obligations. The nature of the financial guarantee is that it is operative throughout the life and de-commissioning of the site. As such, it is not prone to the complexity and inflexibility of attaching different financial guarantees (and indeed different capped amounts) to specific operational phases (pre-operational, operational, pre-decommissioning, de-commissioned, and closed). As such, financial guarantees in respect of landfills are maximally flexible in respect of the period to which the damage applies. There is little evidence that actual damage caused has exceeded the amount specified in waste management permit conditions and so additional payments have not arisen as a remediation requirement.

The possibility exists of private civil action as between the site operator and neighbours that have occasioned damage as a result of the off-site migration of pollution from a landfill site but this is a matter for common law remedies (in nuisance, trespass, negligence, riparian rights or *Rylands v Fletcher*). It is not a matter for regulation as between the Government and the landfill site operator. Arguably, the same situation should apply in relation to CCS storage sites, as the Government is not traditionally seen as the locus for private law-based remedies as between neighbours in analogous circumstances. Such an approach has been taken to CCS liabilities in the Australian context.

3.6.3.1 EU Landfill Directive (1999) – ‘upon site closure’ comparison

3.6.3.1.1 *Operating, Before Site Closure*

Under the Landfill Directive, a site operator must produce a plan of the site and the proposed operations procedure, with staffing, sorting and traffic flows. There are two main issues that this directive looks at, the type of waste placed at the site, and the result to the local water aquifers and ground water. The latter must not be damaged or polluted by the liquid run-off or leachate. A planning or competent authority will monitor the site use and filling.

As a site is used, the plan will show which areas of the site, often a former quarry or pit, will be used and in what order. This will be to allow areas furthest from the entrance to be filled up first, so they can be stabilised and covered as part of the process of capping and making the site dormant after use. However it may be that to reduce run-off, the competent authority wants another order of use, so no leachate gets into the ground or water courses.

When a site is approaching closure, or when the competent authority wants to close it, the operator must give notice and produce a closure plan of how the site will be shut down, covered, waste gases and liquids collected, testing and monitoring, staffing and pollution control. All records must be available to the competent authority, copied or transferred, and a testing regime and site-monitoring plan agreed. An environmental impact statement may be required.

During filling of the site there will be inspections by both operator and the competent authority. There must be communications between both sides, and good record keeping of the fill type, problems, and plans of progress showing where the fill level was at certain dates, with photographs.

Site insurance will be required to meet potential obligations regarding damage, nuisance and long term monitoring. The fee will reflect the financial standing of the site operator.

Depending on the site's size, samples and site monitoring may be carried out regularly by in-house or contract technicians. Air and water samples will be collected to monitor the leachate and gas build up. A team may frequently engage in testing, monitoring and recording the findings. Smaller sites or companies may find it advantageous to use outside help from environmental consultancies with experience in this area.

Once part of the site is filled up to the agreed level, a capping layer will be applied all over the finished area of waste, so that it cannot blow away or attract birds and vermin. This also allows the technicians to move in with their gas collectors, pipes and flare points to start the safe removal and combustion of the methane produced, and if the methane is to be used, e.g. in a site generator, then the pipe work can be built for this. Methane from sewage and waste has been used in generators since the 1960s.

The site operator has to demonstrate sound financial status before starting to operate a facility so that when the site shuts down and income stops, they are able to monitor the site and have the financial standing to carry all their obligations with no site income.

3.6.3.1.2 After site closure

A testing regime will have been agreed between the parties to monitor the site. This will mostly involve scientists, rather than disposal operatives and transport/earthmoving plant. Therefore, there is a change in the type and grade of staff used at each phase, from manual to technical. The staff who worked on the waste tip would be moved or released. The nature of the work has changed from construction to biological science, and the staff used need to change to skilled testing and laboratory technicians.

Communication is still needed with the local planning and waste authorities, so that any problems with methane gas or biological leachate can be overcome. Regular meetings and reports are needed to inform the competent authority supervising the site that there is no risk to the groundwater or the atmosphere.

The cap to the site needs to be finished and sealed to contain the methane produced, which occurs in a dry weather free zero oxygen zones. Methanisation of the waste is needed to reduce the organic parts to inert waste. Requirements are given in Article 14 in the directive.

Methane produced by the decomposing waste tip can be piped off to burners or used in heating or power generation. Landfill waste sites are unlikely to be beside communities, to avoid infestation by vermin, so it is unlikely that the methane produced will go into area heating for flats and offices.

Insurance cover is needed for the long duration of the sealing and inspection period, possibly 20-30 years. This would cover public and employee liability, from methane leaks to injuries, and to indemnify the operator or the authority from any continuing liability.

3.6.3.2 Landfill Site Insurance in Operation

Whilst the site is being filled, parts may be covered to stop waste being blown about by the wind, but being open, there is plenty of area for any waste gases and methane to escape to the air in low concentrations. Whilst in operation, the plant compacts the waste delivered by vehicles to the site. As there will be a height limit set by the local waste and planning authorities, the operator will try to put as much into the site as possible within this limit.

There will be a number of staff and operatives at the site who will be covered by their employers' insurances. Furthermore, the vehicles and the compacting plant will be covered by the vehicles' insurance. Moreover, visitors and inspection testers will be covered by their employers insurances, unless on a public inspection visit and buildings will have insurance in order to cover fire and injury.

Insurers will cover accidents but not the negligent management of the site. In the insurance context, unexpected build ups of methane may be acceptable as an accident, but not if it could have been removed safely. Furthermore, nuisance will not be covered in the insurance.

3.6.3.3 After Closure

The major difference between the closing of a landfill and its operational phase is the presence of people and plant whilst being filled. Once the decision to close the site is taken, these largely disappear. Once the plant has finally compacted the waste and put a capping layer over it, the vehicles, drivers, supervisors and sorting operatives move on to other work. There are no deliveries, except for testing by technicians and pipe and burner installation to remove the methane safely and landscaping staff to hide the site under vegetation.

Plant and site buildings are therefore removed in order to leave a largely rural area. Protection for testing staff and site managers with visitors would be covered by their employers' liability insurance or third party liability insurance. The risks therefore partly go down in this phase, as there is much less activity but also go up in respect to the capping and methane creation, which can cause explosions. Nuisance is not covered, in order to encourage good management.

Insurers need to consider only unforeseen accidents for this phase such as explosions. Bad management and inadequate gas removal are not covered by the insurance. As in the case of Middleton v Wiggins (CA 1995), the insurer successfully won an appeal that the demolition of a house by escaping methane was not an accident in the method of disposal, which was what was insured.

3.6.3.4 Employee Types used in Closure of a Landfill Directive Site

What is not often considered in relation to the operational costs of running facilities that are subject to an environmental permit is personnel requirements. While a myriad of staff and outside experts are involved in the operation phase of a site, there is a sense that de-commissioning and closure phases require little expert time and thus little expense. The staffing issues in these phases have been highlighted, which are somewhat similar to the comparative CCS phases as a means of illustrating that this is a cost intensive aspect of site investment.

On a practical note, when a landfill site closes, and is capped so it takes no further waste, anaerobic decomposition takes place and organic matter degrades to give off methane. As this is explosive and can damage neighbouring property, tests take place to provide information to control the site and gas build up. These tests and control meetings use different staff to the period when the site was operational.

- *Blue Collar Operatives:* With the closure of the site, there is no longer any need for drivers of landfill excavators and bulldozers to compact and move waste into position. Thus the first difference is the loss of blue collar driving jobs, which may not be unskilled as driving construction plant now requires a pass. Sorters and refuse lorry

drivers are also not needed on site, as no waste is arriving.

- *Management:* The operatives' managers are not needed either, as there is no staff to be managed at this site. However for continuity, a few of the landfill management staff should be employed to provide information on meetings, policy and past events.
- *Testing Technicians:* As the closed landfill tip will be giving off methane, so this has to be collected and analysed. Air quality near the tip has to be recorded too, so any complaints of smells or illnesses can be met with data. The local council or planning authority will also want to know there are no problems here. Technicians need to know how to use equipment, how to record measurements, and what the process is to get sound data for compliance with the law and local agreements.
- *Environmental and Biochemical Laboratory Staff:* Once the technicians have collected the samples at the site, they are taken to a laboratory, which may be on site, nearby, or at the premises of a testing company or environmental consultant. Staff are needed to test the samples, and to accurately record the data for analysis, reports and meetings. Tests are for gas and leachate liquid, which can damage ground water under the landfill.
- *Biologists and Environmentalists:* Once the data has been found from the test samples, it needs to be presented to the local planning authority, the waste authority, the council, or the government ministry. Reports using the data are written by specialists, who can decide whether there is a problem or if there needs to be action taken to stop or control a problem.
- *Landscaping:* With the closure of a landfill tip, the top is capped, and landscaped. Partly this is to stop erosion from rain and weather, and to hide the site locally, to reduce complaints. Landscaping staff are needed to do this job, and monitor plant growth, removing any dead trees, weeds or poor grass.
- *Committees:* After a landfill site closes, a committee of the land owner, the site filling contractor, the local authority, local planners and county council, plus environmental advisors from government departments will want to monitor the site as waste settles. Reports are written for this group, so they can monitor and control the decline, methane emissions, and prepare for handover.

3.7 Summary of Regulatory and Legislative Aspects of CCS

This chapter's objective was to develop an understanding of the latest regulatory and legislative developments in the CCS industry. This research was conducted by studying specific risk-related financial and regulatory issues with regards to CCS as well as the ways in which regulatory and legislative aspects of CCS are addressed in other jurisdictions and the lessons that should be learnt from them. Furthermore, this chapter has also compared the oil and gas, nuclear and waste management industries with the CCS industry with regards to the types of risks involved in them and the ways in which those risks are addressed along with the different ways by which they obtain insurance against the risks.

Real-world examples of flexible approaches to CCS regulation can be seen in the case of Norway, Australia, Canada and the USA. Norway has incentivised CCS by legislating a carbon emissions tax of €40 t/CO₂. Furthermore, CCS is regulated both under the Norwegian Pollution Act and the Petroleum Act, at present however, responsibility for leakages is not satisfactorily regulated under Norwegian law. In Australia, the long term liability associated with the storage of CO₂ is covered under the Research Development and Demonstration approval provision under the Victorian Environment Protection Act, which recognises that more comprehensive legislative cover would be necessary in the future for any commercial geo-sequestration projects. Moreover, Canadian legislation, on the other hand, has taken the approach of issuing closure certificates under a new CCS Act with the Government, of the province in question, assuming responsibility for the stored CO₂.

The US EPA has adopted a flexible regulatory approach and has finalised requirements for CCS through the development of permitting for a new class of storage wells (Class VI) to be used specifically for geological storage of CO₂. Furthermore, the EPA has proposed a default 50-year time-frame for CCS liability with the provision that the acting EPA Director may shorten or lengthen that period based on risk data gathered during the permitting process. In addition, this new permitting system will allow for financial guarantees for CCS to be chosen from a variety of different options which would allow for greater market competition and rapid deployment of lower-cost solutions in the CCS industry.

Within the EU, Netherlands and Germany's view towards CCS regulation are seen to be progressive whilst adhering to the letter of the CCS Directive. The Government of the Netherlands plans to implement the CCS Directive by amending the Netherlands Mining Act,

which means that CCS would operate under a Permitting regime (similar to that of the US). Preliminary analysis indicates that liability will lie with the storage license holder, up to the point of the license expiration. If at that point there is a legal successor, or the materials are proven to be definitively left in the subsoil, the liability would be removed from that license holder.

The German Government has indicated that it will adopt a draft act on CCS which would allow it to conduct extensive testing of the technology on the basis of which further requisite implementation and legislation will be drafted. The Act is expected to include the possibility that after a period of 30 years from the decommissioning of a plant, and thus about 80 years after its start-up, operators may transfer their responsibility to the Federal Government (once the operator has established proof of the long-term safety of the storage site). Notably, the CCS Demonstration Project Network which is sponsored by the European Commission has also expressed the belief that long-term CCS liability will be dealt with in the manner of oil spills – with “the state assuming liability after a regulated abandonment process”.

Aside from other self-evident conclusions, what appears from examining the schemes related liability case studies in the nuclear, oil and gas and waste management industries, are more sophisticated approaches to risk management and financial liability sharing. By in large, capped liability schemes are a feature within said case studies and much more investment certainty is in place, even though the risk profiles of these sectors are at least as high as for carbon capture and storage. Furthermore, the nuclear industry actually features a much higher overall risk profile. Additionally, what is also evident for these sectors is a much more receptive response from the insurance sector, which is, arguably, one lynchpin to the long term success of the CCS sector.

The next chapter will review and analyse the latest legislative and regulatory developments and the underlying policy with regards to the CCS industry and the long-term liability of CO₂ storage in general. Furthermore, the next chapter shall explore some financial and regulatory liability issues with regards to CCS along with some forward looking scenarios followed by a comparison of risks between the CCS industry and Oil and Gas, Waste Management and Nuclear industries.

CHAPTER 4

METHODOLOGY

4 METHODOLOGY

4.1 Introduction

This chapter outlines and describes the methods developed and used throughout this study from data collection to risk ranking and characterization. This study has explored the ways in which the environmental risks associated with the storage phase of the CCS chain can be calculated and/or estimated using different methods. This has been achieved using the following three different systems engineering techniques:

1. Fault Tree Analysis (FTA)
2. Analytical Hierarchy Process (AHP)
3. Fuzzy Analytical Hierarchy Process (FAHP)

Background information to the said three methods has been given in the relative sections of chapter 2 of this thesis. Furthermore, the ways in which these three methods work in order to quantify the risks have also been described in this chapter. In summary, the structure of this chapter is as follows:

- **Section 4.2 (Methodological Framework)** describes the overall methodological framework of this thesis and the way in which chapters and section work together towards the final conclusion of the research.
- **Section 4.3 (Fault Tree Analysis, FTA)** describes the ways in which the FTA method works and can be used in order to map the risks associated with CO₂ storage.
- **Section 4.4 (Analytical Hierarchy Process, AHP)** gives an overview of the way in which this method has been used in order to rank the risk elements within the storage phase of CCS and provide us with the significance of each risk in comparison to others.
- **Section 4.5 (Fuzzy Analytical Hierarchy Process, FAHP)** uses the fuzzy logic and fuzzy set theory in order to calculate the importance and the criticality of the risks mapped in this chapter in order to overcome the problem of potentially imprecise judgements and preferences of the experts used in this study.

4.2 Methodological framework

The risks associated with the geological storage of carbon dioxide will be quantified using the FTA, AHP and FAHP methods in conjunction with each other. The way that this analysis is going to be carried out is as follows. Firstly, using the FTA method and having studied the available literature in this area, the risks that can potentially lead to the eventual failure of the caprock hence causing the stored carbon dioxide to leak from underground reservoirs, have been outlined and presented as a fault tree (shown in figure 7 of section 4.3). The risk events shown in figure 7 were presented to experts within academia and industry who were active in the field of underground storage of CO₂. An internet based expert survey was presented to relevant experts via email and social media tools such as Twitter. Furthermore, the expert survey was widely advertised to the experts in relevant conferences, events and by sending it by email through academic research centres and networks such as the UK CCS Research Centre. Detailed information regarding the way in which the surveys were designed, the reasons behind the development of the questions and sending it to the experts have been given in chapter 5 of this thesis. This will be done in order to find out which one of the said risks is significant enough for the insurance industry and regulator to have to allocate more resources to try and reduce them when evaluating the risks. The chosen experts used the AHP method in order to rank the risk events in comparison to each other in a pair-wise manner.

The FTA method along with the expert consultation partially provided the input for the overall quantitative risk analysis methodology of this research. As it was expected at the beginning of this project, the FTA method and the expert surveys also provided the input for the AHP and FAHP methods. The AHP method calculated different importance weights for different risk elements within the fault tree of figure 7. Moreover, the output of the AHP method was also used as input for the FAHP method.

Figure 6 shows a flowchart of the methodological framework for this study. As it is shown in the flowchart, this study includes an iterative process in a sense that the results obtained from the quantitative analyses will be used in order to identify the gaps in knowledge associated with CO₂ storage. At this stage, if it is concluded that there is a gap in the knowledge gathered so far in the literature review of this study, then the process will refer back to the available literature in order to fill those gaps. Having said this, it is not going to be possible to fill all the gaps in knowledge and calculate all the risks involved in CO₂ storage.

4.2.1 Expected Outcomes

As it was explained previously, there is currently no standard regime for insuring commercial scale CO₂ storage facilities owing to the fact that there is not enough information with regards to the type of risks involved in the technology of geological storage of CO₂ and the likelihood of occurrence of those risks.

One means of developing greater confidence in the technology is for regulators to cultivate a sense that CCS is not a high risk activity. In turn, this will lead to the development of a nascent CCS insurance market which in turn would solve a range of current stakeholder challenges around risk and liability.

With regards to the CO₂ storage facility insurance, Zurich Insurance Group Ltd. recently announced that they have developed insurance mechanisms called ‘Carbon Capture and Sequestration Liability Insurance’ and ‘Geologic Sequestration Financial Assurance’ (Ecologist, 2009). The former includes liabilities from pollution events and geomechanical liabilities that might arise during the injection phase whereas the latter guarantees a source of finance to manage affairs after closure of the plant including when a cap is being placed on the closed well and monitoring after closure (Ecologist, 2009).

Whilst these types of policies are beneficial and can potentially motivate the CCS industry to undertake this activity, their drawback is that even though the former insurance policy covers the CO₂ capture facility during the operation phase of the power plant, the latter policy solely covers the storage facility for 10 to 30 years after the wells have been sealed off. However, the entire logic behind the use of this technology in the first place was that CO₂ would be injected into saline aquifers or depleted oil and gas fields and remains there for centuries to come with minimal long-term risk of leakage. The reason as to why this matter may cause the CCS industry to become nervous is because of the lack of knowledge with regards to the existence of companies and/or Governments that were responsible for the CO₂ injection in the first place decades after the storage well has been sealed off.

Therefore, in order for regulators to be able to legislate more effectively and in favour of the CCS technology and as a result persuade the insurance industry to insure storage facilities to cover the long-term risks, they would have to have extensive knowledge of the type of risks involved in the CO₂ storage technology. In doing so, insurance bodies have to be able to

understand and therefore prioritise the risks in accordance with their relative importance and criticality. Not only this enables them to make sure more effort is put in managing the more important risks but also enables them to allocate more resources to more important risks in case of a disaster of some sort which results in CO₂ leakage from storage reservoirs.

One of the aims of this research was to explore different methods that can be used in order to assess the risks associated with storage of CO₂ from a qualitative point of view as well as a quantitative one. In doing so, it was initially expected that the methods used in this study in order to quantify the risks would provide different results to each other since they work in parallel to each other. In other words, they each quantify the risks from a different point of view.

It was further expected that having analysed the results of the quantitative risk analysis from the methods described within this chapter, conclusions can be drawn that could benefit the insurance industry and regulators. This would be in the form of recommendations to the said stakeholders with regards to the probability of occurrence of the risks when storing CO₂ underground and the criticality of those risks should they occur.

The said methods were expected to mathematically and objectively calculate the significance, importance and likelihood of the risks associated with each different scenario when storing CO₂ in comparison with each other. In doing this, one can judge which risks to take and which ones to avoid under uncertainty. This relative assurance can help the insurance companies and regulators better understand the risks and hence adjust their current terms and premiums and legislate more effectively to address the risks of carbon dioxide storage. Figure 6 outlines the methodological framework in a schematic manner.

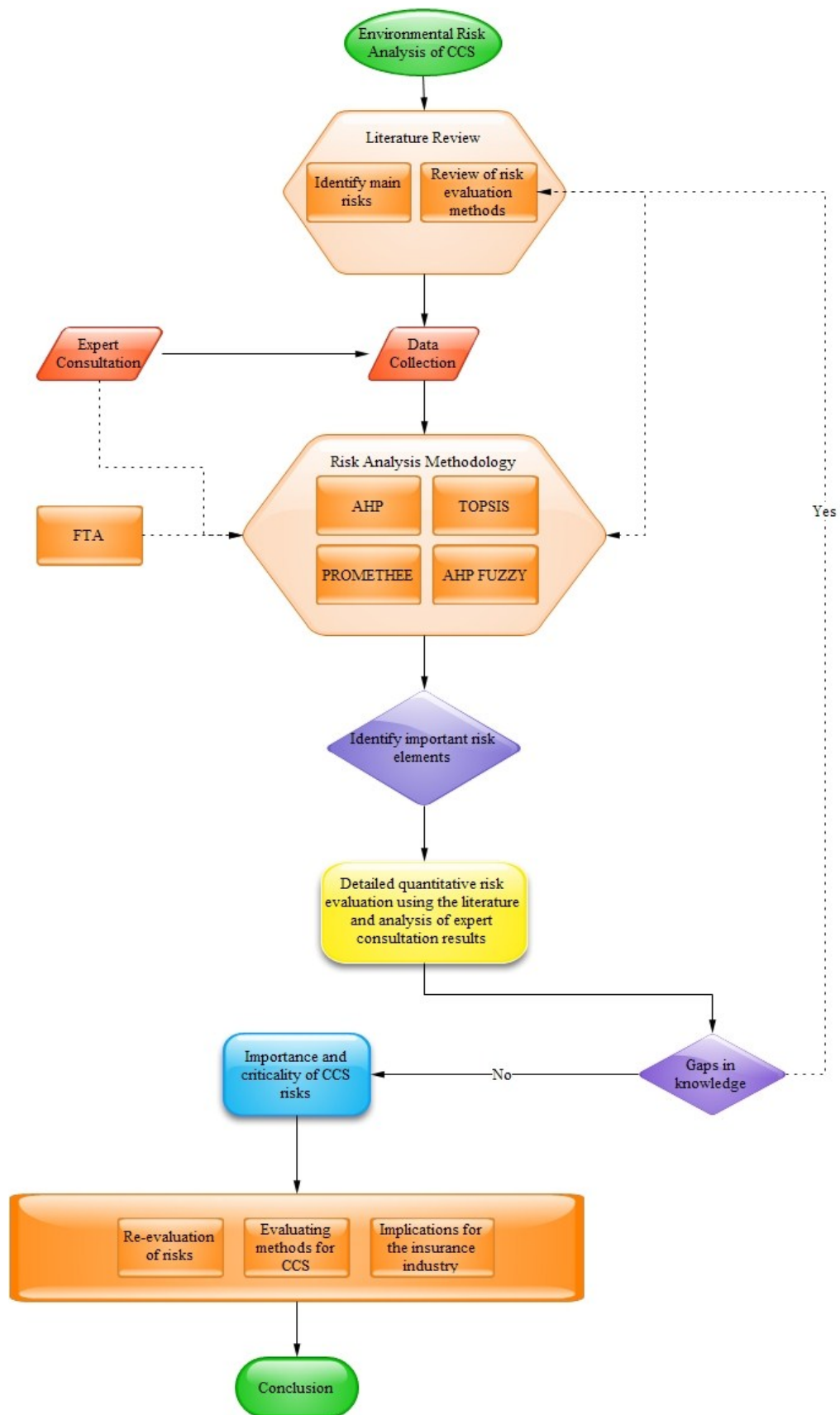


Figure 6, Methodological framework of this research

4.3 Fault Tree Analysis (FTA)

Fault Tree Analysis is a method that has been employed successfully in assessing the impacts of other projects with similar risks as those involved in CCS. Consequently, this method can be used in analysing the impacts of different failure events related to CCS especially after CO₂ has been injected into the reservoir. The FTA method is a presentation of the events that can have devastating impacts to humans' health and the environment at large (Sharma, 2008). The events are connected to bring out the relationship of the events to the risks. Figure 7 represents the use of fault trees in CCS.

The FTA method has been successfully used in many industries which are similar in terms of risk profiles to the CCS industry such as Nuclear, Chemical and Waste Management industries. For example, in the nuclear industry, FTA has been used in order to calculate the probability of a nuclear power plant safety device being unavailable when needed and to calculate the probability of a nuclear power plant accident. Moreover, in the chemical industry FTA has been used to evaluate a chemical process and determining where to monitor the process and establish safety controls.

In the fault tree of this section (figure 7), all the events that can lead to the migration of the stored CO₂ into the subsurface have been presented. The consequence of high pressure during the injection is likely to induce fracturing of the subsurface rocks. However, the impact of this leakage could be localised and limited in time given that pressure is expected to get diminished after a few decades after injection stops. Furthermore, the sub surface rock could fracture at the interface of the storage and caprock leading to leakage of carbon dioxide through the caprock (Van, 2006). The fault tree in figure 7 clearly shows that overpressure could lead to reopening of previously existing fractures and especially were pre-existing but had not been identified. At lower parts of the fault tree, a description of all the events and processes that could occur at the injection level taking into account both normal situations and altered situations can be found. Normal situations are outlined by Farret et al. to include the degradation of the cement lining with passage of time, which may result from various reasons such as usual ageing, chemical reaction with brine while altered situations include poor quality of cement and the junctions on the injection and storage interface. A fault tree shows the probable interactions that may occur; consequently initiating migration of CO₂ during the storage phase of CCS. Another advantage of this type of analysis is that it can help

in defining interactions between activities and occurrences before they are integrated into a numeric model. The software used in fault tree analysis is usually linked to a database where occurrences can be categorized effectively (Farret et al., 2011). These categories could include mechanical processes, chemical processes, thermal processes or categories of those events which could occur in the short term and those which take long to be witnessed.

This method enables us to analyse the risks associated with CO₂ storage in different ways such as:

- Assessing the impact of changing the loss resulting from each event into a distribution, rather than assuming a fixed amount
- Assessing the impact if mitigating actions could be developed for certain events, so that, e.g., the amount of loss were reduced if these events occur (or the probabilities of events are reduced or both)
- Creating dependencies or correlations between the occurrence (and/or magnitude) of some of the events
- Replacing the Binomial distribution with a Poisson distribution so that each event could occur more than once per period.

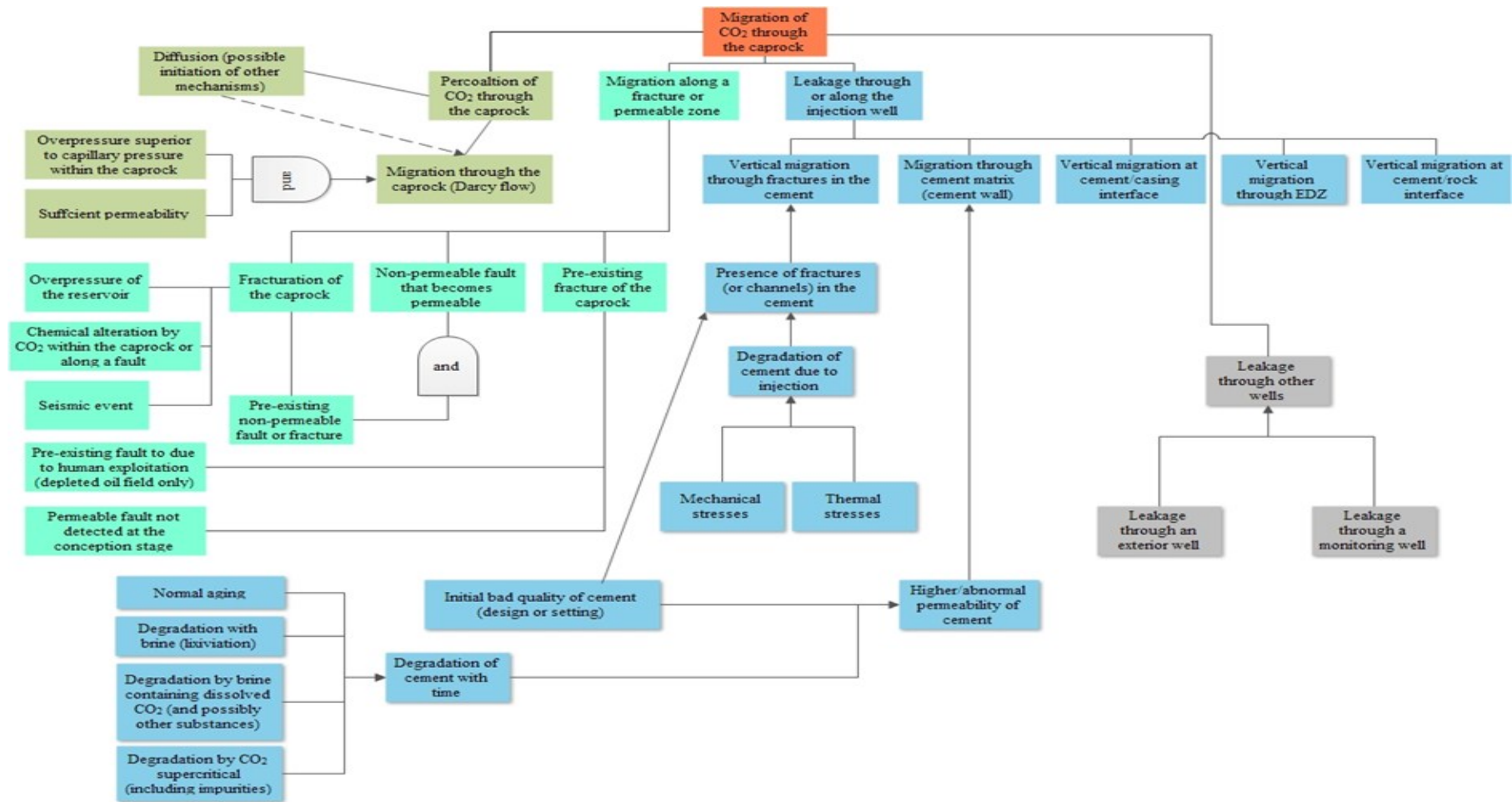


Figure 7, Events that can potentially be combined together in order to contribute towards the leakage of CO₂ from the caprock

For simplicity purposes, each risk element has been renamed as below.

Risk Element	
A	Percolation of CO ₂ through the caprock
B	Migration of CO ₂ along fracture or permeable zone
C	Leakage of CO ₂ through or along the injection wall
D	Leakage of CO ₂ through other wells
a₁	Migration of CO ₂ through the caprock (Darcy flow)
a₂	Diffusion of CO ₂ (possible initiation of other mechanisms)
b₁	Fracturation of the caprock
b₂	Non-permeable fault that becomes permeable
b₃	Pre-existing fracture of the caprock
c₁	Vertical migration of CO ₂ through fractures in cement
c₂	Vertical migration of CO ₂ at cement/casing interface
c₃	Vertical migration of CO ₂ at cement/rock interface
c₄	Vertical migration of CO ₂ through EDZ
c₅	Migration of CO ₂ through cement matrix (cement wall)
d₁	Leakage of CO ₂ through a monitoring well
d₂	Leakage of CO ₂ through an exterior well

Table 7, Name of risk elements in simplified form

The fault tree designed in this section of the thesis (figure 7) shows the potential risk events that could possibly cause the stored CO₂ in the reservoirs to leak through the caprock. The said risk events forming the fault tree have been generated from studying the CCS related literature in general. Table 7 was generated containing the first and second level in the risk hierarchy of the fault tree in order to simplify the calculation process of the probability/likelihood of CO₂ leakage through the caprock.

4.4 Analytical Hierarchy Process (AHP)

4.4.1 How the AHP operates

AHP was invented based on four basic principles. Therefore, all the calculations, rules and regulations are based on these principles. They are as follows:

1. The inverse condition: If the preference of element A to element B is equal to m , then the preference of element B to element A is $\frac{1}{m}$.
2. The homogeneous condition: Element A and element B have to be homogeneous and comparable. In other words, either element cannot be infinite or zero times better than the other.
3. Dependence: A hierarchical element can be attached and dependent in a linear manner to its upper element and this dependency can continue to higher levels.
4. Expectations: Whenever a change occurs in the hierarchical structure, the evaluation process has to be done again.

When you combine individual performance indicators to one key performance indicator, you can give each one a different weight. Now the question is how to derive the weights. AHP derives ratio scales from paired comparisons. It also allows for some small inconsistency in judgments. As an input you can use actual measurements or subjective opinions such as satisfaction feeling or appearance. The output of this method is ratio scales and a consistency index. The method is based on the solution of an Eigen value problem; the ratio scales result from Eigen vectors and the consistency index from the Eigen value.

The process is performed in several steps, which are as follows:

1. A hierarchy tree has to be created defining the Objective, Criteria and sub-criteria.
2. The Decision Making Matrix has to be created based on Saaty's nine point scale which is presented in table 8.

Intensity of Importance	Invers of Intensity of the Importance	Definition	Explanation
9	1/9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
7	1/7	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
5	1/5	Strong importance	Experience and judgment strongly favour one element over another
3	1/3	Moderate importance	Experience and judgment slightly favour one element over another
1	1	Equal importance	Two elements contribute equally to the objective
2, 4, 6 and 8	1/2, 1/4, 1/6 and 1/8	When compromise is needed. Can be used to express intermediate values	
1.1, 1.2, etc.	1/1.1, 1/1.2, etc	Elements that are very close in importance	
Reciprocals		If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	
Rationales		Ratios arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix

Table 8, Fundamental importance scales in AHP (Chen et al., 2007)

3. The Pair-wise Comparison Matrix is created by comparing the elements within the decision making matrix in a pair-wise manner in order to determine the relative importance of the elements with respect to each other. The pair-wise comparison matrix for n elements is presented in equation 6.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}; a_{ij} = \frac{1}{a_{ji}}; a_{ii} = 1; i, j = 1, 2, \dots, n$$

Equation 6, AHP: Pair-wise Comparison Matrix

Where:

- The element a_{ij} can be interpreted as the degree of preference of the i^{th} attribute over the j^{th} attribute and vice versa.
- a_{ij} is the preference of element i to element j and vice versa for a_{ji} . i and j vary at natural numbers set.

4. A Consistency Ratio (CR) is calculated using equation 7.

$$CR = 100(CI / RI)$$

Equation 7, AHP: Consistency Ratio

where CR is consistency ratio, CI is consistency index, RI is random index and n is the number of columns. If $CI/RI < 0.10$, it means that the degree of consistency is satisfactory. If however, $CI/RI > 0.10$, it means that the degree of consistency is not satisfactory. As a result, the AHP comparisons may not have reliable results (Liang, 2003). Furthermore, if CI and CR

are satisfactory, then the preferences are calculated based on normalized values. On the other hand, the procedure has to be repeated until the results fall in the desired range.

5. In this step, the pair-wise comparison matrix is normalised by dividing each element of a column by the sum of all elements within that column. As a result, the sum of all rows within the normalised matrix will be equal to 1. A normalised pair-wise matrix is demonstrated in equation 8.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1J} \\ r_{21} & r_{22} & \cdots & r_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nJ} \end{bmatrix} \quad i=1,2,\dots,n; j=1,2,\dots,J$$

Equation 8, AHP Normalised Pair-wise Matrix

6. In this step, the Relative Weight of each element has to be determined by calculating the arithmetic average of each row.
7. As a result of multiplication of the amount of relative weights of each element by the weights of the criteria of the higher levels, the Elements Weight Vector is obtained. This vector is demonstrated in equation 9.

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}; \sum_{i=1}^n w_i = 1; i=1,2,\dots,n$$

Equation 9, AHP: Element Weight Vector

Where w_i is the weight of the i^{th} element.

The inconsistency ratio is calculated in order to define the level of consistency of judgments of the decision makers. The inconsistency ratio is calculated using equation 10.

$$CI = \frac{\lambda - n}{n - 1}$$

Equation 10, AHP: Inconsistency Ratio

Where $\lambda_{\max}$ is the highest eigenvalue of the pair-wise comparison matrix. Generally, the closer the inconsistency index it is to zero, the greater the consistency will be. Therefore, within the AHP, this index has to be lower than 0.1 in order for the AHP results to be considered as consistent.

How to calculate the weights

In AHP, each element in each level is paired together with its corresponding element in the higher level and then their weights are calculated in comparison with each other. This weight is called the “local priority”. Furthermore, as a result of combining the local priorities (relative weights), the final weight of each item is determined. This weight is called “overall priority”. In this method, experts within the specific field of study, use their judgement in order to compare the elements in a pair-wise manner. The options that they have in order to compare the elements with each other can be seen in figure 8.

Figure 8, shows a graphical representation of the way in which different weights are assigned to different criteria in the AHP.

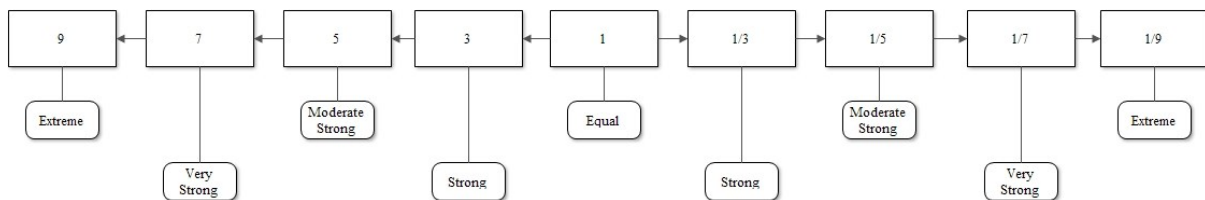


Figure 8, Weight assigning system used in the AHP

In the first instance, a graphical representation (such as a Tree Diagram) of the problem has to be constructed. This diagram has to include the Objective, Criteria and sub-criteria. Figure

7 shows a tree diagram constructed during the course of this study. It shows some of the main events that can be combined together in different ways in order to lead to other events (more serious/significant) and then eventually lead to the leakage of CO₂ through the caprock.

The way in which figure 7 should be interpreted is to consider each event box at the lower end of the tree diagram and follow it through towards the beginning of the diagram in order to inspect the hazards that the chosen event boxes can potentially cause. The diagram has been illustrated using four different colours which correspond to the four main hazards that can lead to the eventual leakage of CO₂ through the caprock. Furthermore, all the other event boxes that lead to the main event boxes are of the same colour.

As described in section 3.1.3 of this chapter, if the preference of element “A” to element “B” is “ m ”, then the preference of element B to element A shall be “ $\frac{1}{m}$ ”. In other words, we start to compare element “A” with element “B” using a scale ranging from 9 to 1/9. Number 1 means that both criteria have the same importance and they are equal. On the other hand, number 9 means that criterion “A” is nine times more important/significant than criterion “B” and therefore, 1/9 means that criterion “B” is nine times more important than criterion “A”.

As a result of these calculations, a ranking is obtained which shows the alternative that has the highest value which has to be chosen as the preferred choice.

4.5 Fuzzy Analytical Hierarchy Process (FAHP)

In this research project, the FAHP method is used in order to rank the different risks within the fault tree developed earlier in this chapter (section 4.3). Similar to the conventional AHP method, the Fuzzy AHP method also involves the creation of a hierarchy that includes a set of alternatives, $M_i (i=1,2,\dots,m)$, criteria that are used for evaluation purposes, $C_j (j=1,2,\dots,n)$, and a final weighting vector, $w=(w_1, w_2 \dots, w_n)$ (Pan, 2008).

Furthermore, the pair-wise comparison matrices have to be converted to fuzzy pair-wise comparison matrices. In order to produce these matrices, the pair-wise comparison matrices

that were used for the AHP method in section 4.4 of this chapter are going to be used. These matrices are created in the exact way that the AHP matrices are created.

This step involves the pair-wise comparison of the members of the decision making matrix. These pair-wise comparison matrices are created in order to determine the relative preferences of the alternatives with respect to each other. The structure of a generic pair-wise comparison matrix comparing the different alternatives of a decision is shown in equation 11.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad a_{ij} = \frac{1}{a_{ji}}, \quad a_{ii} = 1, \quad i, j = 1, 2, \dots, n$$

Equation 11, FAHP: Comparison matrix

The Consistency Index (*CI*) which evaluates the inconsistency of pair-wise comparisons is calculated using equation 12.

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Equation 12: FAHP: Consistency Index (CI)

where λ is an eigenvalue of matrix A and n is the number of columns. In addition, a Consistency Ratio (*CR*) is calculated using equation 13.

$$CR = 100(CI / RI)$$

Equation 13: FAHP: Consistency Ratio (CR)

where CR is the consistency ratio, CI is the consistency index and RI is random index.

Furthermore, following the construction of the hierarchy, Chen and Yang's table (table 8) can be modified to accommodate the Fuzzy AHP technique which is illustrated as table 9.

Intensity of Importance	Definition	Explanation
(8, 9, 10)	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
(6, 7, 8)	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
(4, 5, 6)	Strong importance	Experience and judgment strongly favour one element over another
(2, 3, 4)	Moderate importance	Experience and judgment slightly favour one element over another
(1,1,1)	Equal importance	Two elements contribute equally to the objective
(1,2,3); (3,4,5); (5,6,7) and (7,8,9)	When compromise is needed. Can be used to express intermediate values	Elements that are very close in importance
(0.1,1.1,2.1); (0.2,1.2,2.2) etc.		
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix

Table 9, Fundamental fuzzy importance scales in FAHP

The way in which the FAHP method works is as follows:

1. First step is comprised of the creation of the fuzzy pair-wise comparison matrix. In this step, pair-wise comparison matrices are established using the fuzzy concept and the triangular fuzzy number using the AHP method.

2. According to Enea and Piazza, the most important innovation by Chang was the application of the extent analysis to calculate the synthetical degree value (S_k) (Enea and Piazza, 2004). The way in which extent analysis works is that it supports the decision amongst different goals, which could be in contrast. Chang's proposal defined the value of the fuzzy synthetic extent using the standard fuzzy arithmetic as shown in equation 14.

The calculation of the amount of S_k is as follows. In this step, the S_k amount which is a TFN is calculated for each row of the pair-wise comparison matrix using equation 14.

$$S_k = \sum_{j=1}^n M_{kl} \otimes \left[\sum_{i=1}^m \sum_{j=1}^n M_{ij} \right]^{-1} ; i = 1, 2, \dots, m; j = 1, 2, \dots, n;$$

Equation 14, FAHP: Synthetic extent with respect to the i^{th} object

where k is the number of each row, i and j are indices of the alternative and attribute respectively.

3. The third step consists of the computation of the degree of possibility. In this step, the degree of possibility of different amounts of S_k is calculated. If M_i and M_j are two TFNs, then the degree of possibility of M_i to M_j is calculated using equation 15.

$M_i = (l_i, m_i, u_i) \geq M_j = (l_j, m_j, u_j)$ is defined as:

$$V(M_i \geq M_j) = \sup_{y \geq x} [\min(\mu_{M_j}(x), \mu_{M_i}(y))]$$

Equation 15, FAHP: Degree of possibility

The degree of possibility can be equivalently expressed as follow:

$$V(M_i \geq M_j) = \text{hgt}(M_j \cap M_i) = \begin{cases} 1, & m_i \geq m_j \\ \frac{u_i - l_j}{(u_i - l_j) + (m_j - m_i)}, & l_j \leq u_i, i, j = 1, 2, \dots, n; j \neq i \\ 0, & l_j \geq u_i \end{cases}$$

Equation 16, FAHP: Equivalent form of the degree of possibility

Where $M_i = (l_i, m_i, n_i)$, $M_j = (l_j, m_j, n_j)$ and $V(M_i \geq M_j)$ is the degree of possibility of M_i to M_j . Moreover, figure 9 shows the degree of possibility.

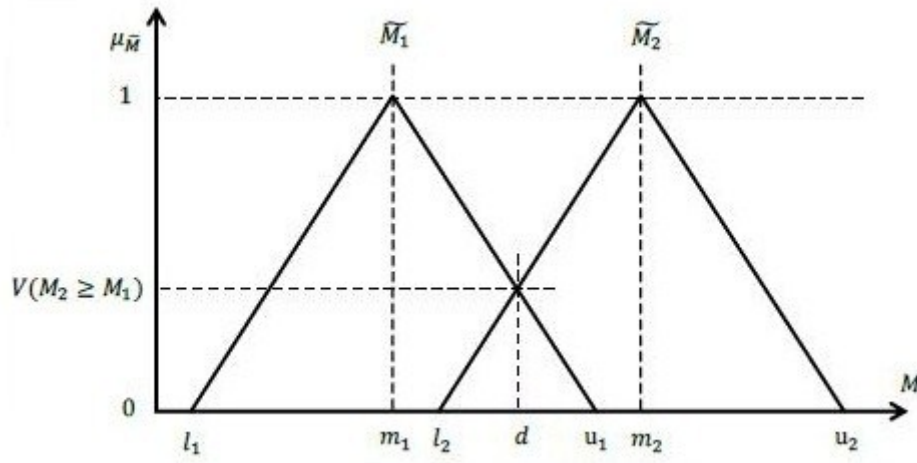


Figure 9, FAHP: Degree of possibility (Büyüközkan et al., 2004)

The degree of possibility of a TFN from other TFNs is calculated using equation 17.

$$V(M_1 \geq M_2, \dots, M_k) = [V(M_1 \geq M_2) \dots V(M_1 \geq M_k)]$$

Equation 17, FAHP: Degree of possibility of a TFN from other S_k TFNs

where k is the index of the last TFN.

4. In the fourth step, the weights of the different criteria are calculated using equation 18.

$$W'(x_i) = \text{Min}\{V(S_i \geq S_k)\}, i = 1, 2, \dots, k; k = 1, 2, \dots, n; k \neq i$$

Equation 18, FAHP: Calculation of the weights

where $W'(x_i)$ is the desired weight.

Furthermore, the vector of the weight is calculated using equation 19.

$$W' = [W'(c_1), W'(c_2), \dots, W'(c_n)]^T$$

Equation 19, FAHP: Vector of weight

where W' is the vector of the weight of the attributes.

5. In this step, the vector of the weight of the normalized attributes is obtained. Moreover, the vector of the weight of the normalized attributes is created when equation 20 is applied.

$$w_i = \frac{w'_i}{\sum_{j=1}^n w'_j}, i, j = 1, 2, \dots, n$$

Equation 20, FAHP: Vector of normalised attributes

where i is the index of each attribute and n is the number of all attributes.

6. This step contains the calculation of the relative importance coefficients of the alternatives and ranking them. The relative importance coefficients are produced by multiplying the weights of the attributes to the achieved weights of the alternatives with respect to each attribute. Furthermore, it is concluded in this step that an alternative which has a greater relative importance coefficient, has the most significance amongst alternatives.

The next chapter describes the way in which the stakeholder consultation stage of this research took place using expert surveys that were sent out to the experts within academia and the CCS industry. Chapter 5 also explains how the results of the surveys are going to be interpreted in a way that they would be useful for the risk analysis sections described in chapter 4.

CHAPTER 5

EXPERT

CONSULTATION

5 EXPERT CONSULTATION

5.1 Introduction

As part of this research project, an expert survey was designed and presented to expert individuals within the field of carbon dioxide storage under geological formations. Furthermore, the expert survey was sent to experts within academia and the CCS industry.

This chapter outlines the way in which the expert survey was designed, conducted and the means by which it was presented to the experts. Furthermore, the ways in which that the survey results were used to conduct the quantitative risk analysis has also been described.

5.2 Carbon Dioxide Storage Experts

The strategy behind the selection of the participants within this study was to choose the national and international experts, institutions and companies that had expertise and specialised in the field of carbon dioxide storage underground based on previous projects that they had been involved in as well as on-going ones.

When distributing the surveys, it was made sure that to the extent that was possible, they were distributed evenly within experts that were active in academia and the CCS industry. Furthermore, to the extent to which was possible, the survey was also distributed evenly within national and international experts. This was done in order to obtain a balanced expert opinion with regards to the questions within the survey. However, despite presenting the survey evenly amongst national and international experts, disappointingly the international experts and companies did not take part in the study to the extent that was expected.

Table 133 (Appendix III) shows a list of national and international experts that were chosen to take part in this research project. Moreover, the rationales behind the inclusion of said experts within this study have also been included in table 133.

National and international companies, institutions and research centres were chosen based on the expertise of their members in the field of CO₂ storage. Furthermore, since these companies were different in size in comparison to each other, therefore, in some cases more than one expert contributed to the survey.

5.3 Means of Contacting the Experts

The survey was designed, published on www.surveymethods.com and distributed amongst industrial and academic experts that were chosen (shown in table 133 of Appendix III) via email and social media such as Twitter. Furthermore, experts within the field of CO₂ storage were also approached in two CCS related conferences namely the 11th International Conference on Greenhouse Gas Technologies (GHGT-11)⁴ which was held from 18th of November to 22nd of November 2012 in Kyoto – Japan (The GHGT 2012 conference was attended by 1293 delegates) and the UK Carbon Capture and Storage Research Centre's (UKCCSRC) Early Career Researcher Annual Meeting 2013 which was held from 1st of July to 2nd of July 2013 in Newcastle – UK.

Some of the experts were contacted and recruited directly whereas some other ones were contacted and recruited indirectly using targeted advertisements through social media and emails through academic research centres. For example, the UKCCSRC advertised extensively for the expert survey by sending emails with a link to the survey to their research centre members as well as their network members inviting them to take part in the survey of this study. The UKCCSRC's network members consist of some 900 international experts across all CCS related topic areas within academia, industry and governmental organisations (Cathcart, 2013). In addition, the UKCCSRC posted a message on their Twitter account advertising the survey of this research which can be seen in figure 10. Furthermore, the same message was also advertised on UKCCSRC's website⁵ – which was exclusively available to the centre's members – as well as on their blog.

⁴ <http://www.ghgt.info/index.php/Content-GHGT11/ghgt-11-overview.html>

⁵ <http://www.ukccsrc.ac.uk/>



Figure 10, Twitter message posted by UKCCSRC advertising the expert survey

5.4 Expert Survey Design

The expert survey was designed using the Survey Methods Inc.⁶. Furthermore, amongst different packages within the company, the “Advanced” package was purchased due to the relative length and sophisticated nature of the survey.

The survey was designed in a way that required the experts to answer 22 questions. Furthermore, each question presented a potential failure mechanism (risk event) at the beginning of the question followed by two potential sub-events. Based on their expertise, the experts were asked to select the option that they believed was more likely to cause the occurrence of the main risk event in that particular question. Moreover, they were also asked to state to what extent that sub-events/sub-risk was more likely to cause the failure of the main risk event in question using the scale that was given to them. This scale can be seen in table 11 created by Chen and his colleagues in 2007. Furthermore, the format of the survey was such that the experts were first asked to make their pairwise comparisons between the risk events and then comment on their selection in the following question.

Table 10 shows an example of the type of survey that was distributed to the experts. As evident from the table, experts were asked to rank risk elements in comparison with each other in a pair-wise manner using the scales outlined in table 11.

⁶ www.surveymethods.com

Table 10 merely shows one of the questions within the expert survey. The complete survey can be seen in section 10.2.1 (Appendix II).

Pair-wise comparison of the main criteria:

Please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

Please use the scale below to rank the risks from 1 to 9.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Percolation of CO₂ through the caprock or B: Migration of CO₂ along fracture or permeable zone	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Percolation of CO₂ through the caprock or B: Leakage of CO₂ through or along the injection well	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Percolation of CO₂ through the caprock or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Migration of CO₂ along fracture or permeable zone or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Migration of CO₂ along fracture or permeable zone or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Leakage of CO₂ through or along the injection well or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 10, an example of the type of surveys used in the stakeholder consultation stage

As evident from table 11, the scale that experts used in order to complete the survey consisted of numbers ranging from 9 to 1/9. The rationale for using such ranking system has been given in section 4.4 of the Methodology chapter.

Intensity of Importance	Invers of Intensity of the Importance	Definition	Explanation
9	1/9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
7	1/7	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
5	1/5	Strong importance	Experience and judgment strongly favour one element over another
3	1/3	Moderate importance	Experience and judgment slightly favour one element over another
1	1	Equal importance	Two elements contribute equally to the objective
2, 4, 6 and 8	1/2, 1/4, 1/6 and 1/8	When compromise is needed. Can be used to express intermediate values	
1.1, 1.2, etc.	1/1.1, 1/1.2, etc	Elements that are very close in importance	
Reciprocals		If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i .	
Rationales		Ratios arising from the scale	If consistency were to be forced by obtaining n numerical value to span the matrix

Table 11, Fundamental importance scales in AHP (Chen et al., 2007)

Figure 11 shows an outline of all the risk events (on the first and second level of the overall risk tree of figure 7, section 4.3) that could potentially cause the leakage of CO₂ from storage reservoirs.

The questions within the expert survey (Appendix II) were designed in a way that enabled the experts to compare each risk element within figure 11 with other risk elements in a pair-wise way. In addition, it has to be noted that expert stakeholders were asked to complete the surveys taking into account only the first and second level in the overall risk hierarchy of the fault tree in order to simplify the calculation process of the probability/likelihood of CO₂ leakage through the caprock. Figure 11 shows the said simplified version of the overall fault tree developed in this research.

This exercise was carried out in order to obtain a ranking system for the potential risks that can cause the leakage of the stored CO₂ from underground storage reservoirs. As explained before, this ranking is performed based on the importance and criticality of the said risks. The experts performed this ranking procedure using Saaty's importance scales system (table 10). A full explanation with regards to the way in which the pair-wise comparisons have to be carried out and the reasons behind this procedure has been given in chapters 2 and 4 (Risk Analysis and Methodology chapters respectively).

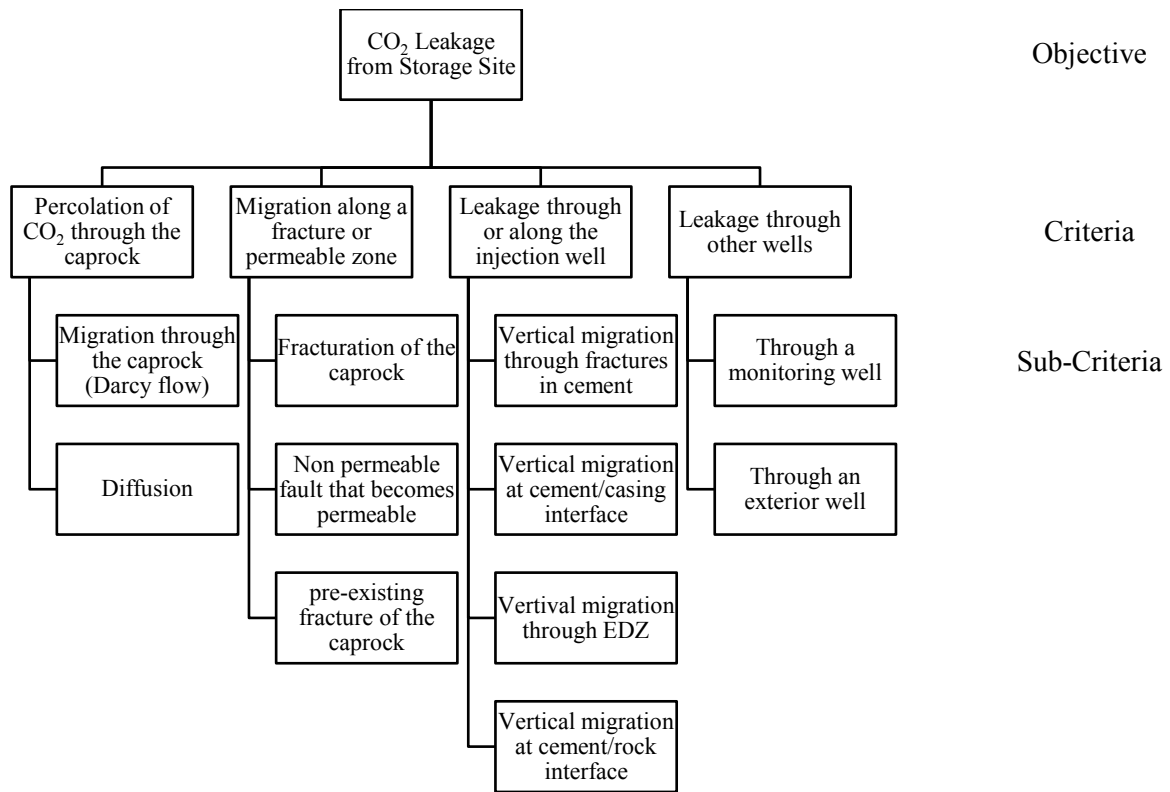


Figure 11, all the events (1st and 2nd levels) that can lead to the migration of the stored CO₂ into the subsurface

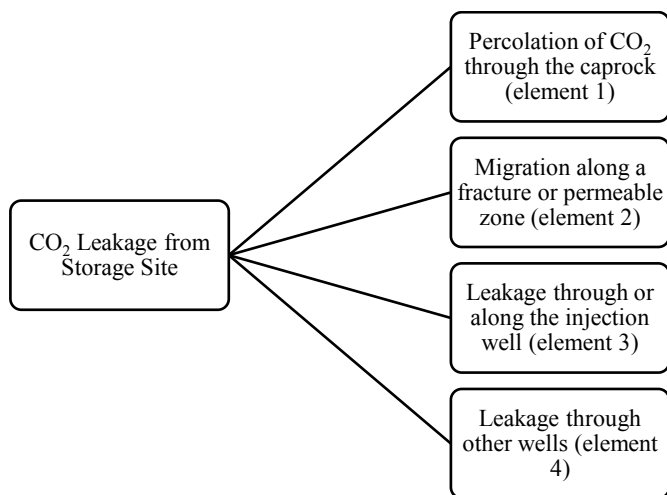


Figure 12, the objective and the criteria within the main fault tree of this project

A sample of the expert survey which was sent to the experts along with the email message that accompanied the survey inviting the experts to take part have been attached as appendices of this thesis (Appendix III).

The sample survey shows the format of the survey, the ways in which questions were asked from the experts and the choices/options that they had whilst answering the questions.

5.5 Conclusion

As part of this research project, an expert survey was designed and presented to carbon dioxide storage experts within academic institutions and companies that were active in the CO₂ storage field (name of experts have been shown in table 133 of Appendix III). The experts were asked to compare different risk events associated with the leakage of CO₂ from underground storage reservoirs in a pairwise manner. Moreover, they were asked to do so in order to assess the risk elements presented within the fault tree (developed and presented in figure 7 of section 4.3) and subsequently rank them in accordance with their significance in comparison to each other towards the leakage of CO₂ from storage reservoirs.

The results obtained following expert consultation have been used as input parameters for the two risk analysis methods described in detail in sections 2.6 and 2.7 of chapter 2 and sections 4.4 and 4.5 of chapter 4.

These methods, namely AHP and FAHP were used in order to quantitatively estimate the effect that each risk element had on the eventual risk element (at the top of the fault tree) which is the leakage of CO₂ from underground storage reservoirs.

To the extent that was possible, it was made sure that the survey was distributed evenly amongst national and international experts within academia and the industry. Disappointingly however, not as many international experts took part in this study as it was anticipated in comparison with national experts.

Expert stakeholders were asked to complete the surveys taking into account only the first and second level in the overall risk hierarchy in order to simplify the risk analysis calculation process. In retrospect however, it would have been easier in survey terms to only focus upon risks on the first level of the fault tree, carry out the risk analysis procedure, interpret the results of the AHP and AHP Fuzzy calculations to trace the source of the risk and then perhaps apply the same procedure to the second, third and fourth levels in future research.

5.5.1 Filtering the responses

Overall, the survey was responded to by 55 reliable experts. In other words, there were instances that some participants answered the survey in a way that was not reliable. For example, some participants selected either number 9 or number 1 on the scale described in table 10 for all of the questions within the questionnaire in order to express their personal opinion/objection towards the CCS technology in general. The reason as to why it was decided that the said responses were not reliable is that, as mentioned in the methodology chapter, within the methods used, choosing number 9 signifies the fact that one risk is extremely more significant or important than the other one. In this case, it does not make sense that one would choose number 9 for all the risks. Moreover, choosing number 1 for all the risks signifies the fact that all the risks are equally significant and important which again is inaccurate.

The said problem was further confirmed by studying the comments that they had made within the survey. For example, one participant stated in the comments area that: “At present there is not enough known about the risk of leakage or leakage methods to provide any adequate analysis of the importance of one method from another. In that sense they are all equally important.”

Responses such as the ones above were discarded since they were all in contradiction with each other and therefore were categorised as unreliable results.

The next chapter presents the results that were obtained as a result of using the output of the expert survey as input parameters for the quantitative risk analysis techniques used in this research project.

CHAPTER 6

RESULTS

6 RESULTS

6.1 Introduction

This chapter contains the results of the analyses carried out during the course of this research project in order to quantify the risks associated with the storage of CO₂ under geological formations. Furthermore, this chapter includes the results obtained using the AHP and Fuzzy version of the AHP techniques in order to assess the criticality and importance of individual risk elements involved within the storage phase of CCS technology. The results will be presented in separate sub-sections depending on the method used to obtain them.

6.2 Analytical Hierarchy Process (AHP)

The AHP method was used in order to quantify the importance of each risk element within the fault tree shown in figure 7 (section 4.3) of the Methodology chapter (chapter 4) in comparison with other risk elements. Figure 13 shows a tree diagram representing all the events (on the first and second levels of the fault tree of figure 7) that can lead to the migration of stored CO₂ from underground storage reservoirs into the subsurface. In order to achieve this goal, the importance and criticality of the risk events on the first and second levels of the diagram have been calculated using the output data from the expert consultation stage of the project and the AHP method. Furthermore, as described before in chapter 4, the results obtained from the expert consultation stage of the research have been used as input parameters for the techniques used in this research.

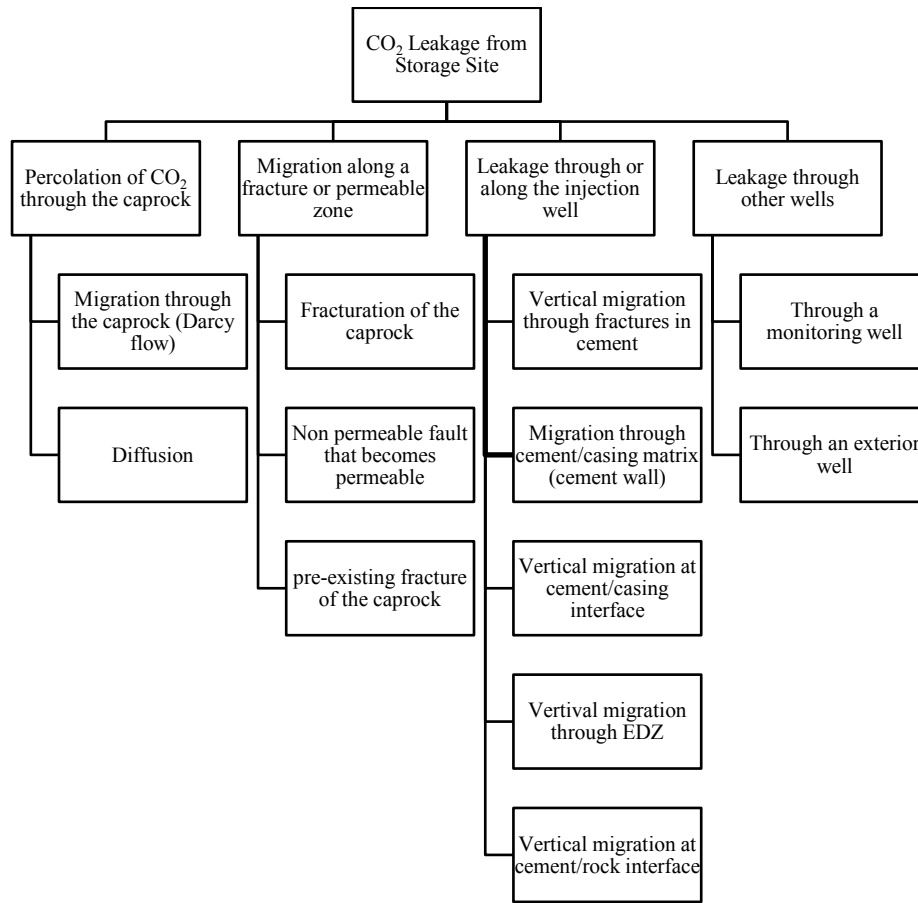


Figure 13, Events (1st and 2nd levels) that can lead to the migration of stored CO₂ into subsurface

As described in chapter 5 of this thesis, an internet based academic survey was developed and presented to academic and industry experts within the field of CO₂ storage under geological formations.

The output of the surveys were then analysed and used as input parameters for the AHP algorithm. As explained in chapter 5, experts were asked to compare the risks that CO₂ storage can potentially entail in a pairwise manner in comparison to other risks within the main fault tree of figure 7.

Table 12 shows the selected branch of the tree diagram of figure 13 in a matrix form. Where,

1. X₁, represents the “percolation of CO₂ through the caprock”,
2. X₂, represents the “migration of CO₂ along a fracture or permeable zone”,
3. X₃, represents the “leakage of CO₂ through or along the injection well”, and
4. X₄, represents the “leakage of CO₂ through other wells”.

5. a_n , represents the importance scales developed by Saaty which have been illustrated in table 7 of section 4.3 (Saaty, 1978b).

It should be noted that, for example, a_{12} refers to the comparison of the element in row 1 and column 2 of the matrix.

	X_1	X_2	X_3	X_n
X_1	a_{11}	a_{12}	a_{13}	a_{1n}
X_2	a_{21}	a_{22}	a_{23}	a_{2n}
X_3	a_{31}	a_{32}	a_{33}	a_{3n}
X_n	a_{n1}	a_{n2}	a_{n3}	a_{nn}

Table 12, General form of the matrix completed by the industrial and academic experts

Experts assigned numbers to each risk element in accordance to their importance, criticality and preference with respect to the ultimate goal which was the leakage of CO₂ through the caprock of the storage reservoir. Furthermore, they were asked to rank each pair of elements in comparison with the other element. Table 12 is a generic matrix that was completed using the experts' answers to the questions that they were asked during the stakeholder consultation phase of this project.

The final weight of each item in a hierarchical process is obtained by adding the results of the multiplication of each criterion's weight. The weights of the criteria reflect the importance of setting the goal and the weight of each element compared to the criteria represents its importance in that criteria.

There are many ways in which the local priorities can be estimated. However, one of the most accurate and common ones is by using the arithmetic average method. The arithmetic average method is performed in three steps. These steps are the following:

Step 1: The numerical values of the elements are added to each other.

	X_1	X_2	X_3	X_n
X_1	1	a_{12}	a_{13}	a_{1n}
X_2	a_{21}	1	a_{23}	a_{2n}
X_3	a_{31}	a_{32}	1	a_{3n}
X_n	a_{41}	a_{42}	a_{43}	1
Sum of columns	$1+a_{21}+a_{31}+a_{n1}$	$a_{12}+1+a_{32}+a_{n2}$	$a_{13}+a_{23}+1+a_{n3}$	$a_{14}+a_{24}+a_{34}+1$

Table 13, AHP matrix showing the addition of numerical values

Step 2: In order to normalise the elements of the matrix, each element in the pair-wise comparisons has to be divided by the sum of all elements.

	X_1	X_2	X_3	X_n
X_1	$1 / (1+a_{21}+a_{31}+a_{n1})$	$a_{12} / (a_{12}+1+a_{32}+a_{n2})$	$a_{13} / (a_{13}+a_{23}+1+a_{n3})$	$a_{14} / (a_{14}+a_{24}+a_{34}+1)$
X_2	$a_{21} / (1+a_{21}+a_{31}+a_{n1})$	$1 / (a_{12}+1+a_{32}+a_{n2})$	$a_{23} / (a_{13}+a_{23}+1+a_{n3})$	$a_{24} / (a_{14}+a_{24}+a_{34}+1)$
X_3	$a_{31} / (1+a_{21}+a_{31}+a_{n1})$	$a_{32} / (a_{12}+1+a_{32}+a_{n2})$	$1 / (a_{13}+a_{23}+1+a_{n3})$	$a_{34} / (a_{14}+a_{24}+a_{34}+1)$
X_n	$a_{41} / (1+a_{21}+a_{31}+a_{n1})$	$a_{42} / (a_{12}+1+a_{32}+a_{n2})$	$a_{43} / (a_{13}+a_{23}+1+a_{n3})$	$1 / (a_{14}+a_{24}+a_{34}+1)$

Table 14, AHP matrix showing the normalised numerical values

Step 3: In the third step of this process, the average value for each row of the normalised comparison matrices have to be calculated.

	X_1	X_2	X_3	X_n	Average	Weight (%)
X_1	$1 / (1+a_{21}+a_{31}+a_{n1})$	$a_{12} / (a_{12}+1+a_{32}+a_{n2})$	$a_{13} / (a_{13}+a_{23}+1+a_{n3})$	$a_{14} / (a_{14}+a_{24}+a_{34}+1)$	B ₁	B₁*100
X_2	$a_{21} / (1+a_{21}+a_{31}+a_{n1})$	$1 / (a_{12}+1+a_{32}+a_{n2})$	$a_{23} / (a_{13}+a_{23}+1+a_{n3})$	$a_{24} / (a_{14}+a_{24}+a_{34}+1)$	B ₂	B₂*100
X_3	$a_{31} / (1+a_{21}+a_{31}+a_{n1})$	$a_{32} / (a_{12}+1+a_{32}+a_{n2})$	$1 / (a_{13}+a_{23}+1+a_{n3})$	$a_{34} / (a_{14}+a_{24}+a_{34}+1)$	B ₃	B₃*100
X_n	$a_{41} / (1+a_{21}+a_{31}+a_{n1})$	$a_{42} / (a_{12}+1+a_{32}+a_{n2})$	$a_{43} / (a_{13}+a_{23}+1+a_{n3})$	$1 / (a_{14}+a_{24}+a_{34}+1)$	B _n	B_n*100
Total	1.00	1.00	1.00	1.00	1.00	100

Table 15, AHP matrix showing the average value of each normalised row

Having performed the said steps, one can obtain a weight for each risk element using the AHP algorithm in order to inspect which risks are of higher significance and criticality and therefore need to be taken into account more in comparison with less significant ones.

The way in which AHP works is that it first calculates the weights and the subsequent rankings of the criteria with respect to the objective or goal. Secondly, it compares the alternatives pair-wise with respect to other alternatives within the fault tree and as a result calculates a subsequent weight for the alternatives.

All the other risk elements within the fault tree were analysed in the same way as above. Moreover, risk elements were analysed and compared with one another with respect to the ultimate goal which was the leakage of CO₂ from the storage reservoir.

The said analyses were carried out using the “Expert Choice” software which was acquired for use within this research. The first criterion that was used within the software and the final results of the AHP method are shown below. In addition, the step by step calculation that was carried out using the Expert Choice software has been given in section 10.1.3 of Appendix I of this thesis.

Figure 14 shows criterion “a₁”, Migration of CO₂ through the caprock (Darcy flow), being analysed using the numerical scale of the AHP technique. On the other hand, figure 15 shows the same analyses with a different scale. Moreover, in the case of figure 15, the linguistic equivalent of the numerical scale has been used.

Note 1: Refer to table 8 of section 3.4.1 for a full list of linguistic equivalents of the numerical values in AHP method’s scale.

During this process, each alternative, namely “A”, “B”, “C” and “D” were compared to each other with respect to the criteria, “a₁”, “a₂”, “b₁”, “b₂”, “b₃”, “c₁”, “c₂”, “c₃”, “c₄”, “c₅”, “d₁” and “d₂”.

Note 2: For a full list of equivalents for the risk elements within the fault tree of this study, refer to table 7 of section 4.3.

Note 3: Numbers in “Red” represent the invers function in AHP.

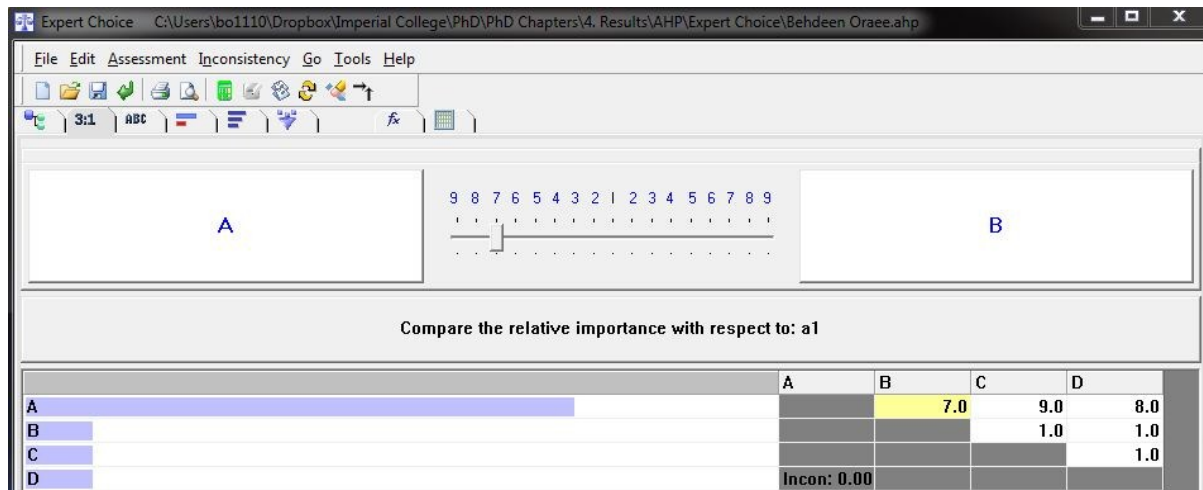


Figure 14, Comparison of alternatives with respect to " a_1 " using a numerical scale

Figure 15 shows the final weight of each alternative with respect to criterion a_1 . The same analyses have been carried out for other criteria, i.e. a_2 , " b_1 ", " b_2 ", " b_3 ", " c_1 ", " c_2 ", " c_3 ", " c_4 ", " c_5 ", " d_1 " and " d_2 " in appendix I of this thesis.

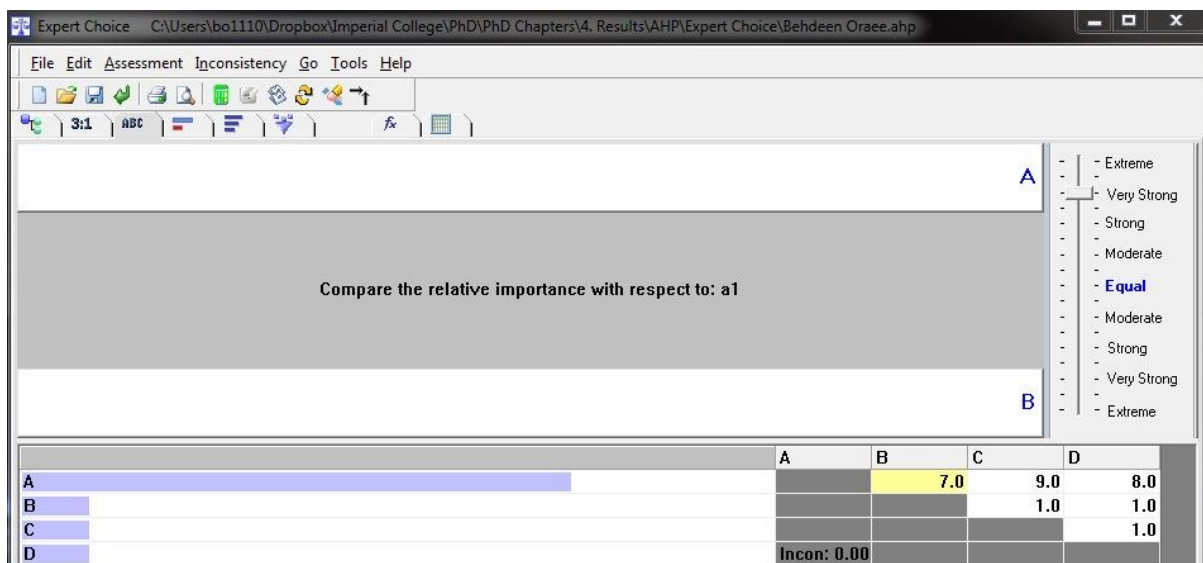


Figure 15, Comparison of alternatives with respect to " a_1 " using a linguistic scale

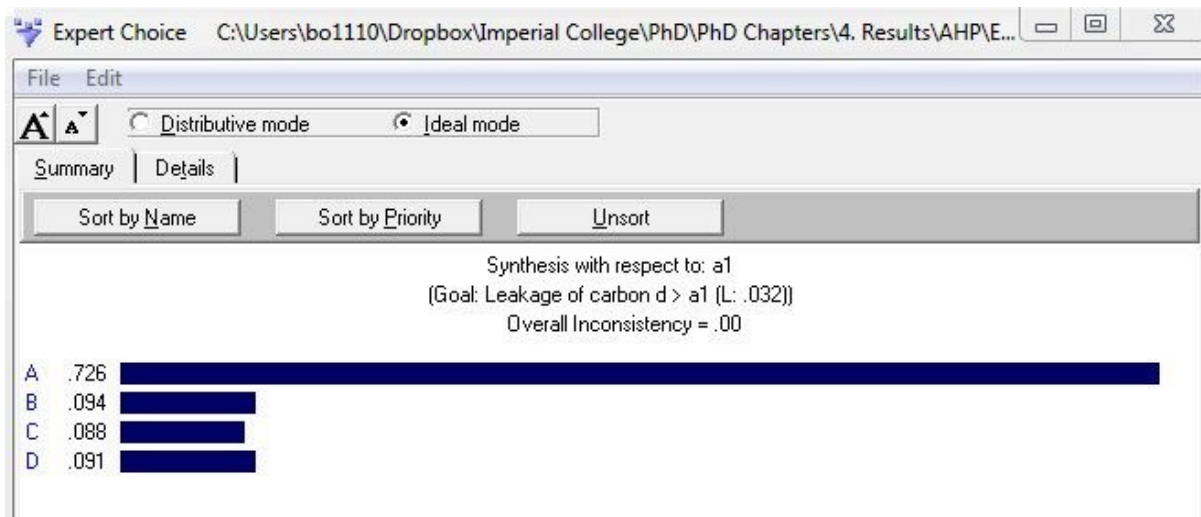


Figure 16, Final weight of alternatives with respect to "a₁"

Figures 17, 18, 19 and 20 show the final steps of the AHP method which was implemented using the Expert Choice software. Moreover, they show the comparison matrix of the criteria using the numerical scale, comparison matrix of the criteria using the linguistic scale and the weight of each criterion in comparison to other criteria respectively.

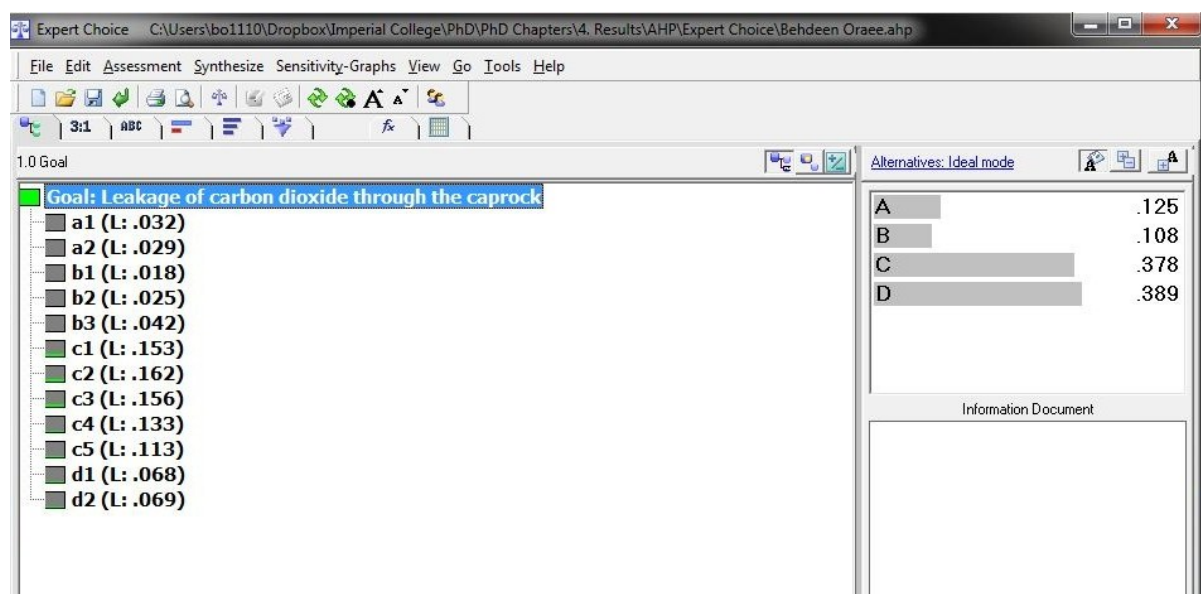


Figure 17, Expert Choice workspace

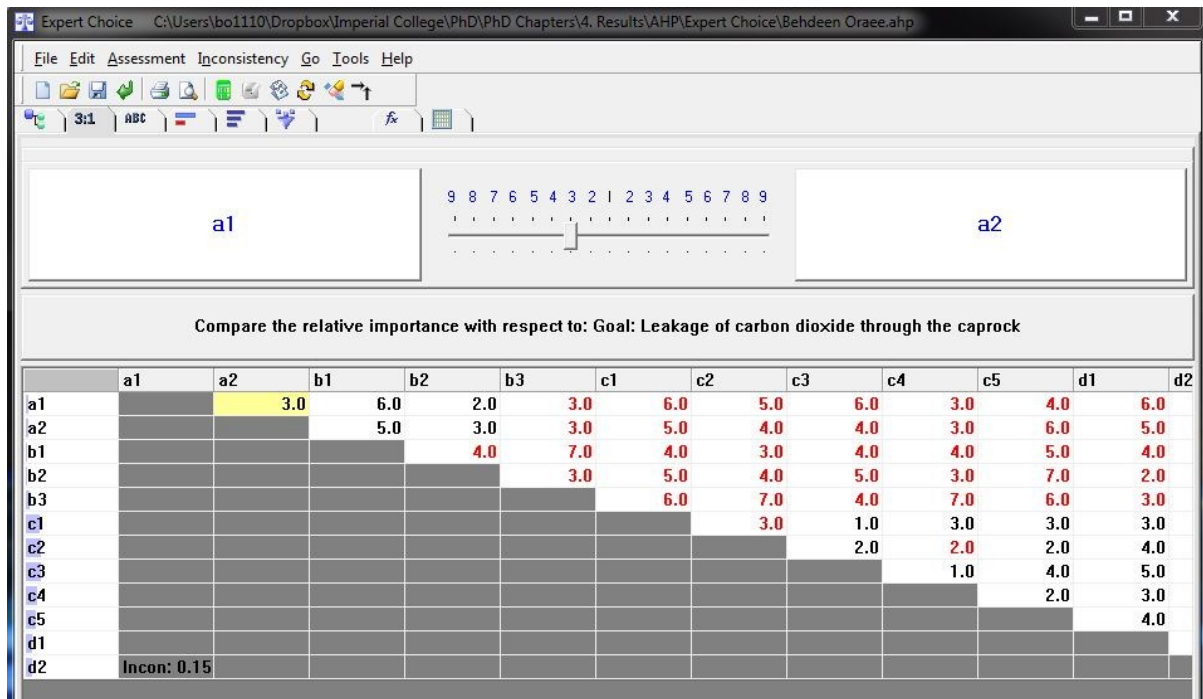


Figure 18, Comparison of each criterion with respect to other criteria using a numerical scale

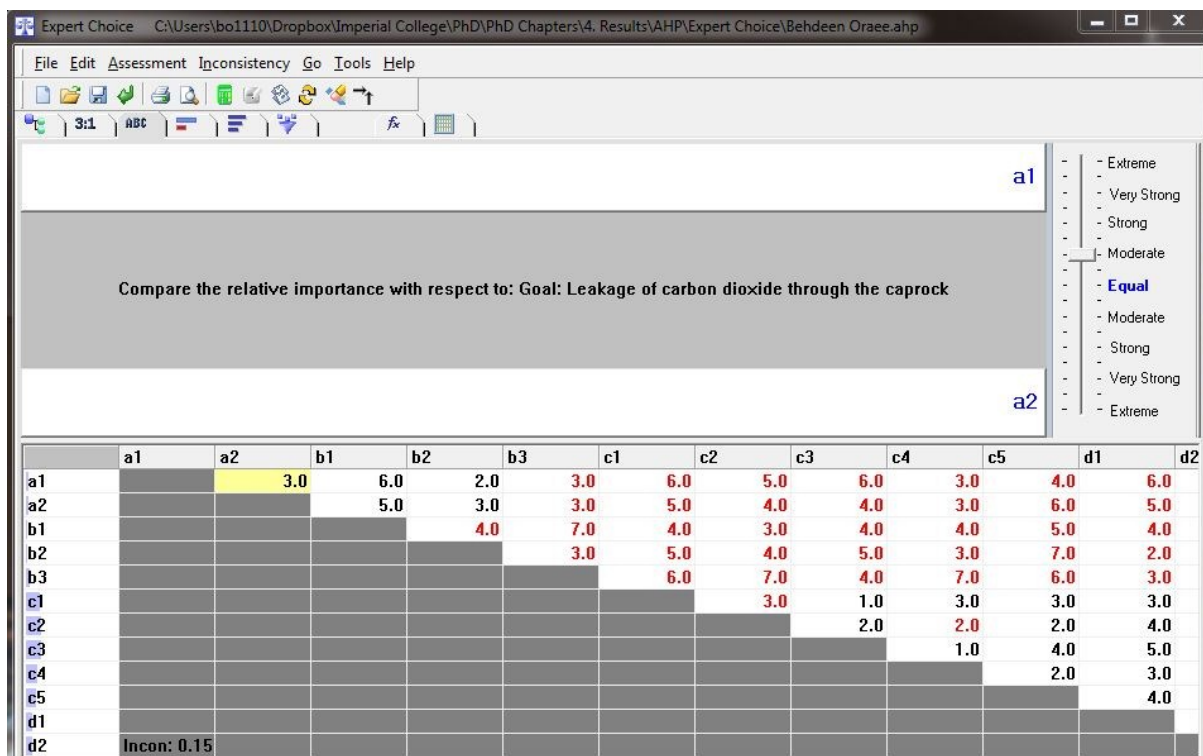


Figure 19, Comparison of each criterion with respect to other criteria using a linguistic scale

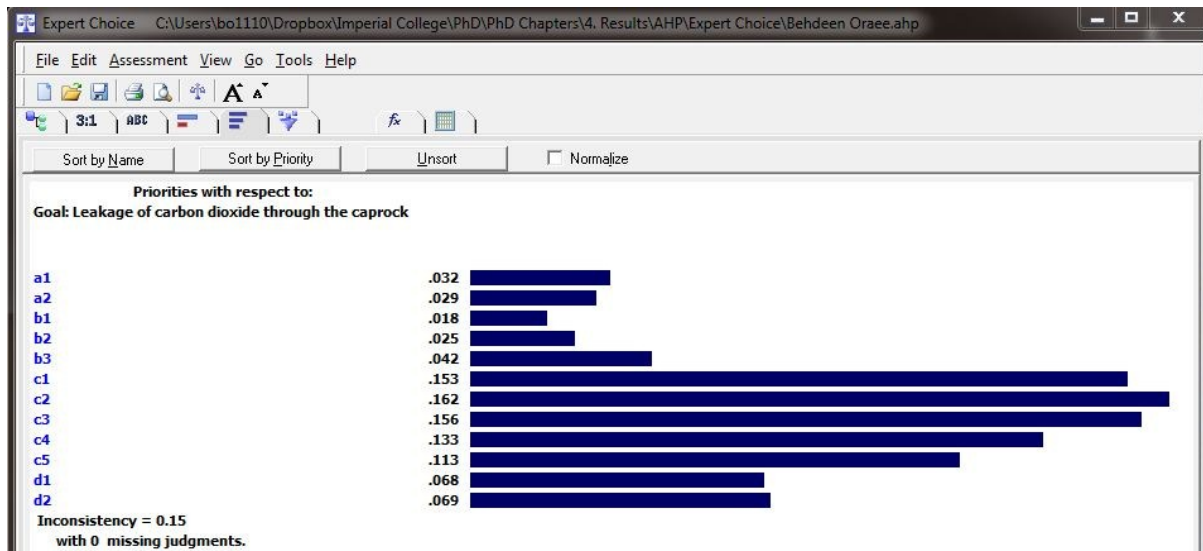


Figure 20, Final weight of each criterion with respect to other criteria

Figure 21 shows the final weight for each main risk element within the fault tree of this study obtained as a result of using the AHP technique.

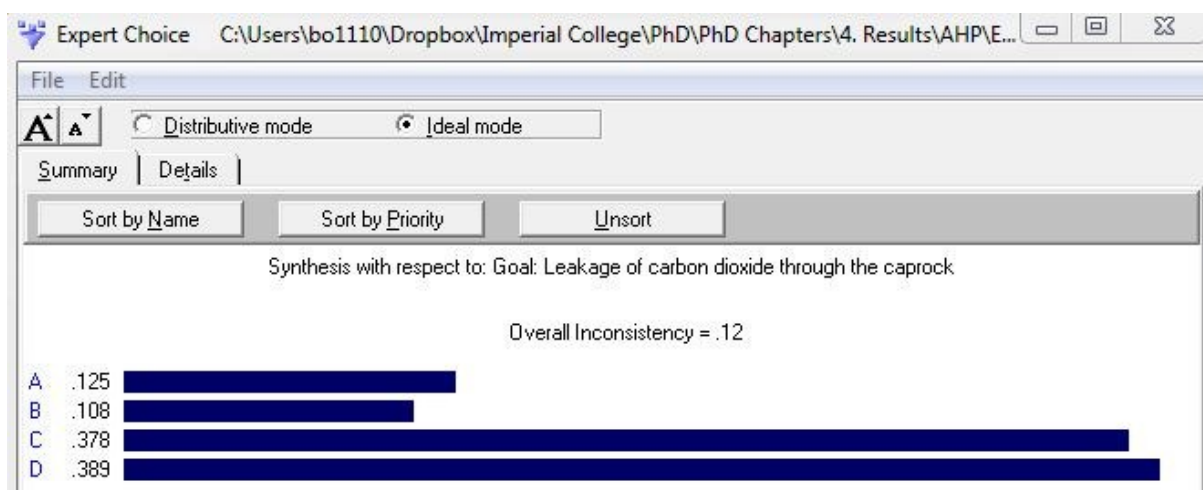


Figure 21, Final weight of the alternatives with respect to each other

Furthermore, tables 16 and 17 show the weight and the subsequent rank of the different risk elements that were analysed in this research using the AHP technique.

Risk ranking of the alternatives	
A	0.125
B	0.108
C	0.378
D	0.389

Table 16, Weight of the risks using AHP

Risk ranking of the alternatives	Rank
Percolation of CO ₂ through the caprock (A)	3
Migration of CO ₂ along a fracture or permeable zone (B)	4
Leakage of CO ₂ through or along the injection well (C)	2
Leakage of CO ₂ through other wells (D)	1

Table 17, Ranking of the risks using AHP

6.3 Fuzzy Analytical Hierarchy Process (FAHP)

As mentioned before, the Fuzzy AHP method was used in order to account for the inherent subjectivity and ambiguity that comes with human judgment. As such, the FAHP provided a type of sensitivity analysis in order to inspect whether or not the results of the AHP method would change should the input parameter be varied slightly.

In this section, similar to the results of the AHP method, the first criterion that was used within the calculation steps for the FAHP method and the final results of the FAHP method are shown. In addition, the step by step calculation that was carried out using the said technique has been given in section 10.1.4 of Appendix I of this thesis.

Table 18 shows the fuzzified version of the comparison matrix of the risks that were studied and shown in figure 7. Tables 19 to 26 show the different steps that have to be taken in order to calculate the weights of the criteria using the fuzzy analysis.

AHP Fuzzy												
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2
a1	(1,1,1)	(2,3,4)	(5,6,7)	(1,2,3)	(1/4,1/3,1/2)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	(1/8,1/7,1/6)
a2	(1/4,1/3,1/2)	(1,1,1)	(4,5,6)	(2,3,4)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/7,1/6,1/5)
b1	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1,1,1)	(1/5,1/4,1/3)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/5,1/4,1/3)
b2	(1/3,1/2,1)	(1/4,1/3,1/2)	(3,4,5)	(1,1,1)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/8,1/7,1/6)	(1/3,1/2,1)	(1/4,1/3,1/2)
b3	(2,3,4)	(2,3,4)	(6,7,8)	(2,3,4)	(1,1,1)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/4,1/3,1/2)	(1/3,1/2,1)
c1	(5,6,7)	(4,5,6)	(3,4,5)	(4,5,6)	(5,6,7)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	(2,3,4)	(2,3,4)	(1,2,3)
c2	(4,5,6)	(3,4,5)	(2,3,4)	(3,4,5)	(6,7,8)	(2,3,4)	(1,1,1)	(1,2,3)	(1/3,1/2,1)	(1,2,3)	(3,4,5)	(1,2,3)
c3	(5,6,7)	(3,4,5)	(3,4,5)	(4,5,6)	(3,4,5)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(3,4,5)	(4,5,6)	(3,4,5)
c4	(2,3,4)	(2,3,4)	(3,4,5)	(2,3,4)	(6,7,8)	(1/4,1/3,1/2)	(1,2,3)	(1,1,1)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)
c5	(3,4,5)	(5,6,7)	(4,5,6)	(6,7,8)	(5,6,7)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,1,1)	(3,4,5)	(2,3,4)
d1	(5,6,7)	(4,5,6)	(3,4,5)	(1,2,3)	(2,3,4)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,1,1)	(1,2,3)
d2	(6,7,8)	(5,6,7)	(4,5,6)	(2,3,4)	(1,2,3)	(1/3,1/2,1)	(1/3,1/2,1)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)

Table 18, Fuzzy pair-wise comparison matrix for the studied risks within this project

Row Number	$\sum_{j=1}^n M_{kl}$
1	(10.42, 13.76, 17.35)
2	(8.77, 11.23, 14.07)
3	(3.05, 3.54, 4.37)
4	(6.33, 8.13, 11)
5	(14.32, 18.70, 23.57)
6	(3.25, 39.33, 48.50)
7	(27.33, 37.50, 48.00)
8	(31.33, 39.50, 48.00)
9	(23.25, 32.33, 41.50)
10	(30.12, 37.58, 45.83)
11	(18.07, 24.37, 30.92)
12	(20.70, 26.42, 33.33)
$\sum_{i=1}^m \sum_{j=1}^n M_{kl}$	(223.93, 292.40, 366.43)
$\left[\sum_{i=1}^m \sum_{j=1}^n M_{kl} \right]^{-1}$	(0.0027, 0.0034, 0.0044)

Table 19, Sum of TFNs of each row of the Fuzzy pair-wise comparison matrix in order to obtain the Fuzzy synthetic extent, S_k

Row Number	$S_k = \sum_{j=1}^n M_{kl} \otimes \left[\sum_{i=1}^m \sum_{j=1}^n M_{ij} \right]^{-1}$	S_k
1	(10.42, 13.76, 17.35) * (0.00272, 0.00342, 0.00446)	(0.02844, 0.04706, 0.07748)
2	(8.77, 11.23, 14.07) * (0.00272, 0.00342, 0.00446)	(0.02393, 0.03842, 0.06282)
3	(3.05, 3.54, 4.37) * (0.00272, 0.00342, 0.00446)	(0.00833, 0.01212, 0.01950)
4	(6.33, 8.13, 11) * (0.00272, 0.00342, 0.00446)	(0.01726, 0.02779, 0.04912)
5	(14.32, 18.70, 23.57) * (0.00272, 0.00342, 0.00446)	(0.03908, 0.06396, 0.10524)
6	(3.25, 39.33, 48.50) * (0.00272, 0.00342, 0.00446)	(0.08255, 0.13452, 0.21658)
7	(27.33, 37.50, 48.00) * (0.00272, 0.00342, 0.00446)	(0.07459, 0.12825, 0.21435)
8	(31.33, 39.50, 48.00) * (0.00272, 0.00342, 0.00446)	(0.08551, 0.13509, 0.21435)
9	(23.25, 32.33, 41.50) * (0.00272, 0.00342, 0.00446)	(0.06345, 0.11058, 0.18532)
10	(30.12, 37.58, 45.83) * (0.00272, 0.00342, 0.00446)	(0.08219, 0.12854, 0.20467)
11	(18.07, 24.37, 30.92) * (0.00272, 0.00342, 0.00446)	(0.04930, 0.08333, 0.13806)
12	(20.70, 26.42, 33.33) * (0.00272, 0.00342, 0.00446)	(0.05649, 0.09035, 0.14885)

Table 20, Achieved TFNs for S_k s of each row of the Fuzzy pair-wise comparison matrix

Criteria	TFNs	Sum of Rows												Sum	Inverse	S _k	
a1	1	1.00	2.00	5.00	1.00	0.25	0.14	0.17	0.14	0.25	0.20	0.14	0.13	10.42	223.93	0.00272	0.02844
	2	1.00	3.00	6.00	2.00	0.33	0.17	0.20	0.17	0.33	0.25	0.17	0.14	13.76	292.40	0.00342	0.04706
	3	1.00	4.00	7.00	3.00	0.50	0.20	0.25	0.20	0.50	0.33	0.20	0.17	17.35	366.43	0.00446	0.07748
a2	1	0.25	1.00	4.00	2.00	0.25	0.17	0.20	0.20	0.25	0.14	0.17	0.14	8.77		0.00272	0.02393
	2	0.33	1.00	5.00	3.00	0.33	0.20	0.25	0.25	0.33	0.17	0.20	0.17	11.23		0.00342	0.03842
	3	0.50	1.00	6.00	4.00	0.50	0.25	0.33	0.33	0.50	0.20	0.25	0.20	14.07		0.00446	0.06282
b1	1	0.14	0.17	1.00	0.20	0.13	0.20	0.25	0.20	0.20	0.17	0.20	0.20	3.05		0.00272	0.00833
	2	0.17	0.20	1.00	0.25	0.14	0.25	0.33	0.25	0.25	0.20	0.25	0.25	3.54		0.00342	0.01212
	3	0.20	0.25	1.00	0.33	0.17	0.33	0.50	0.33	0.33	0.25	0.33	0.33	4.37		0.00446	0.01950
b2	1	0.33	0.25	3.00	1.00	0.25	0.17	0.20	0.17	0.25	0.13	0.33	0.25	6.33		0.00272	0.01726
	2	0.50	0.33	4.00	1.00	0.33	0.20	0.25	0.20	0.33	0.14	0.50	0.33	8.13		0.00342	0.02779
	3	1.00	0.50	5.00	1.00	0.50	0.25	0.33	0.25	0.50	0.17	1.00	0.50	11.00		0.00446	0.04912
b3	1	2.00	2.00	6.00	2.00	1.00	0.14	0.13	0.20	0.13	0.14	0.25	0.33	14.32		0.00272	0.03908
	2	3.00	3.00	7.00	3.00	1.00	0.17	0.14	0.25	0.14	0.17	0.33	0.50	18.70		0.00342	0.06396
	3	4.00	4.00	8.00	4.00	1.00	0.20	0.17	0.33	0.17	0.20	0.50	1.00	23.57		0.00446	0.10524
c1	1	5.00	4.00	3.00	4.00	5.00	1.00	0.25	1.00	2.00	2.00	2.00	1.00	30.25		0.00272	0.08255
	2	6.00	5.00	4.00	5.00	6.00	1.00	0.33	1.00	3.00	3.00	3.00	2.00	39.33		0.00342	0.13452
	3	7.00	6.00	5.00	6.00	7.00	1.00	0.50	1.00	4.00	4.00	4.00	3.00	48.50		0.00446	0.21658
c2	1	4.00	3.00	2.00	3.00	6.00	2.00	1.00	0.33	1.00	3.00	1.00	3.00	27.33		0.00272	0.07459
	2	5.00	4.00	3.00	4.00	7.00	3.00	1.00	2.00	0.50	2.00	4.00	2.00	37.50		0.00342	0.12825
	3	6.00	5.00	4.00	5.00	8.00	4.00	1.00	3.00	1.00	3.00	5.00	3.00	48.00		0.00446	0.21435
c3	1	5.00	3.00	3.00	4.00	3.00	1.00	0.33	1.00	3.00	4.00	3.00	3.00	31.33		0.00272	0.08551
	2	6.00	4.00	4.00	5.00	4.00	1.00	0.50	1.00	4.00	5.00	4.00	4.00	39.50		0.00342	0.13509
	3	7.00	5.00	5.00	6.00	5.00	1.00	1.00	1.00	5.00	6.00	5.00	5.00	48.00		0.00446	0.21435
c4	1	2.00	2.00	3.00	2.00	6.00	0.25	1.00	1.00	1.00	1.00	2.00	2.00	23.25		0.00272	0.06345
	2	3.00	3.00	4.00	3.00	7.00	0.33	2.00	1.00	1.00	2.00	3.00	3.00	32.33		0.00342	0.11058
	3	4.00	4.00	5.00	4.00	8.00	0.50	3.00	1.00	1.00	3.00	4.00	4.00	41.50		0.00446	0.18532
c5	1	3.00	5.00	4.00	6.00	5.00	0.25	0.33	0.20	0.33	1.00	3.00	2.00	30.12		0.00272	0.08219
	2	4.00	6.00	5.00	7.00	6.00	0.33	0.50	0.25	0.50	1.00	4.00	3.00	37.58		0.00342	0.12854
	3	5.00	7.00	6.00	8.00	7.00	0.50	1.00	0.33	1.00	1.00	5.00	4.00	45.83		0.00446	0.20467
d1	1	5.00	4.00	3.00	1.00	2.00	0.25	0.20	0.17	0.25	0.20	1.00	1.00	18.07		0.00272	0.04930
	2	6.00	5.00	4.00	2.00	3.00	0.33	0.25	0.20	0.33	0.25	1.00	2.00	24.37		0.00342	0.08333
	3	7.00	6.00	5.00	3.00	4.00	0.50	0.33	0.25	0.50	0.33	1.00	3.00	30.92		0.00446	0.13806
d2	1	6.00	5.00	4.00	2.00	1.00	0.33	0.33	0.20	0.25	0.25	0.33	1.00	20.70		0.00272	0.05649
	2	7.00	6.00	5.00	3.00	2.00	0.50	0.50	0.25	0.33	0.33	0.50	1.00	26.42		0.00342	0.09035
	3	8.00	7.00	6.00	4.00	3.00	1.00	1.00	0.33	0.50	0.50	1.00	1.00	33.33		0.00446	0.14885

Table 21, Fuzzy pair-wise comparison matrix for the studied risks within this project along with achieved TFNs for the S_k s

S_k			
	l	m	u
S1	0.0284	0.0471	0.0775
S2	0.0239	0.0384	0.0628
S3	0.0083	0.0121	0.0195
S4	0.0173	0.0278	0.0491
S5	0.0391	0.0640	0.1052
S6	0.0826	0.1345	0.2166
S7	0.0746	0.1283	0.2143
S8	0.0855	0.1351	0.2143
S9	0.0634	0.1106	0.1853
S10	0.0822	0.1285	0.2047
S11	0.0493	0.0833	0.1381
S12	0.0565	0.0903	0.1489

Table 22, TFN values of S_k for each criteria

Using equation 32 in section 4.7, the degree of possibility is calculated.

$V(M_1 \geq M_2)$							
s1 $\succcurlyeq$ s2	1	s4 $\succcurlyeq$ s1	0.517754	s7 $\succcurlyeq$ s1	1	s10 $\succcurlyeq$ s1	1
s1 $\succcurlyeq$ s3	1	s4 $\succcurlyeq$ s2	0.703314	s7 $\succcurlyeq$ s2	1	s10 $\succcurlyeq$ s2	1
s1 $\succcurlyeq$ s4	1	s4 $\succcurlyeq$ s3	1	s7 $\succcurlyeq$ s3	1	s10 $\succcurlyeq$ s3	1
s1 $\succcurlyeq$ s5	0.694343	s4 $\succcurlyeq$ s5	0.217345	s7 $\succcurlyeq$ s4	1	s10 $\succcurlyeq$ s4	1
s1 $\succcurlyeq$ s6	0	s4 $\succcurlyeq$ s6	0	s7 $\succcurlyeq$ s5	1	s10 $\succcurlyeq$ s5	1
s1 $\succcurlyeq$ s7	0.034314	s4 $\succcurlyeq$ s7	0	s7 $\succcurlyeq$ s6	0.954586	s10 $\succcurlyeq$ s6	0.953280
s1 $\succcurlyeq$ s8	0	s4 $\succcurlyeq$ s8	0	s7 $\succcurlyeq$ s8	0.949587	s10 $\succcurlyeq$ s7	1
s1 $\succcurlyeq$ s9	0.180894	s4 $\succcurlyeq$ s9	0	s7 $\succcurlyeq$ s9	1	s10 $\succcurlyeq$ s8	0.947859
s1 $\succcurlyeq$ s10	0	s4 $\succcurlyeq$ s10	0	s7 $\succcurlyeq$ s10	0.997848	s10 $\succcurlyeq$ s9	1
s1 $\succcurlyeq$ s11	0.437141	s4 $\succcurlyeq$ s11	0	s7 $\succcurlyeq$ s11	1	s10 $\succcurlyeq$ s11	1
s1 $\succcurlyeq$ s12	0.326527	s4 $\succcurlyeq$ s12	0	s7 $\succcurlyeq$ s12	1	s10 $\succcurlyeq$ s12	1
s2 $\succcurlyeq$ s1	0.799166	s5 $\succcurlyeq$ s1	1	s8 $\succcurlyeq$ s1	1	s11 $\succcurlyeq$ s1	1
s2 $\succcurlyeq$ s3	1	s5 $\succcurlyeq$ s2	1	s8 $\succcurlyeq$ s2	1	s11 $\succcurlyeq$ s2	1
s2 $\succcurlyeq$ s4	1	s5 $\succcurlyeq$ s3	1	s8 $\succcurlyeq$ s3	1	s11 $\succcurlyeq$ s3	1
s2 $\succcurlyeq$ s5	0.481687	s5 $\succcurlyeq$ s4	1	s8 $\succcurlyeq$ s4	1	s11 $\succcurlyeq$ s4	1
s2 $\succcurlyeq$ s6	0	s5 $\succcurlyeq$ s6	0.243302	s8 $\succcurlyeq$ s5	1	s11 $\succcurlyeq$ s5	1
s2 $\succcurlyeq$ s7	0	s5 $\succcurlyeq$ s7	0.322815	s8 $\succcurlyeq$ s6	1	s11 $\succcurlyeq$ s6	0.520257
s2 $\succcurlyeq$ s8	0	s5 $\succcurlyeq$ s8	0.217153	s8 $\succcurlyeq$ s7	1	s11 $\succcurlyeq$ s7	0.585585
s2 $\succcurlyeq$ s9	0	s5 $\succcurlyeq$ s9	0.472693	s8 $\succcurlyeq$ s9	1	s11 $\succcurlyeq$ s8	0.503816
s2 $\succcurlyeq$ s10	0	s5 $\succcurlyeq$ s10	0.263062	s8 $\succcurlyeq$ s10	1	s11 $\succcurlyeq$ s9	0.732509
s2 $\succcurlyeq$ s11	0.231257	s5 $\succcurlyeq$ s11	0.742760	s8 $\succcurlyeq$ s11	1	s11 $\succcurlyeq$ s10	0.552790
s2 $\succcurlyeq$ s12	0.108587	s5 $\succcurlyeq$ s12	0.648844	s8 $\succcurlyeq$ s12	1	s11 $\succcurlyeq$ s12	0.920852
s3 $\succcurlyeq$ s1	0	s6 $\succcurlyeq$ s1	1	s9 $\succcurlyeq$ s1	1	s12 $\succcurlyeq$ s1	1
s3 $\succcurlyeq$ s2	0	s6 $\succcurlyeq$ s2	1	s9 $\succcurlyeq$ s2	1	s12 $\succcurlyeq$ s2	1
s3 $\succcurlyeq$ s4	0.124974	s6 $\succcurlyeq$ s3	1	s9 $\succcurlyeq$ s3	1	s12 $\succcurlyeq$ s3	1
s3 $\succcurlyeq$ s5	0	s6 $\succcurlyeq$ s4	1	s9 $\succcurlyeq$ s4	1	s12 $\succcurlyeq$ s4	1
s3 $\succcurlyeq$ s6	0	s6 $\succcurlyeq$ s5	1	s9 $\succcurlyeq$ s5	1	s12 $\succcurlyeq$ s5	1
s3 $\succcurlyeq$ s7	0	s6 $\succcurlyeq$ s7	1	s9 $\succcurlyeq$ s6	0.811063	s12 $\succcurlyeq$ s6	0.600137
s3 $\succcurlyeq$ s8	0	s6 $\succcurlyeq$ s8	0.9956700	s9 $\succcurlyeq$ s7	0.862382	s12 $\succcurlyeq$ s7	0.662060
s3 $\succcurlyeq$ s9	0	s6 $\succcurlyeq$ s9	1	s9 $\succcurlyeq$ s8	0.802852	s12 $\succcurlyeq$ s8	0.586035
s3 $\succcurlyeq$ s10	0	s6 $\succcurlyeq$ s10	1	s9 $\succcurlyeq$ s10	0.851719	s12 $\succcurlyeq$ s9	0.808450
s3 $\succcurlyeq$ s11	0	s6 $\succcurlyeq$ s11	1	s9 $\succcurlyeq$ s11	1	s12 $\succcurlyeq$ s10	0.635780
s3 $\succcurlyeq$ s12	0	s6 $\succcurlyeq$ s12	1	s9 $\succcurlyeq$ s12	1	s12 $\succcurlyeq$ s11	1
s1 $\succcurlyeq$ s2	1	s4 $\succcurlyeq$ s1	0.517754	s7 $\succcurlyeq$ s1	1	s10 $\succcurlyeq$ s1	1
s1 $\succcurlyeq$ s3	1	s4 $\succcurlyeq$ s2	0.703314	s7 $\succcurlyeq$ s2	1	s10 $\succcurlyeq$ s2	1
s1 $\succcurlyeq$ s4	1	s4 $\succcurlyeq$ s3	1	s7 $\succcurlyeq$ s3	1	s10 $\succcurlyeq$ s3	1
s1 $\succcurlyeq$ s5	0.694343	s4 $\succcurlyeq$ s5	0.217345	s7 $\succcurlyeq$ s4	1	s10 $\succcurlyeq$ s4	1

Table 23, FAHP: Degree of possibility of different amounts of S_k for the TFNs

$V(M_i \geq M_j)$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	1.0000	1.0000	1.0000	1.0000	0.6943	0.0000	0.0343	0.0000	0.1809	0.0000	0.4371	0.3265
S2	0.7992	1.0000	1.0000	1.0000	0.4817	0.0000	0.0000	0.0000	0.0000	0.0000	0.2313	0.1086
S3	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
S4	0.5178	0.7033	1.0000	1.0000	0.2173	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
S5	1.0000	1.0000	1.0000	1.0000	1.0000	0.2433	0.3228	0.2172	0.4727	0.2631	0.7428	0.6488
S6	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9957	1.0000	1.0000	1.0000	1.0000
S7	1.0000	1.0000	1.0000	1.0000	1.0000	0.9546	1.0000	0.9496	1.0000	0.9978	1.0000	1.0000
S8	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
S9	1.0000	1.0000	1.0000	1.0000	1.0000	0.8111	0.8624	0.8029	1.0000	0.8517	1.0000	1.0000
S10	1.0000	1.0000	1.0000	1.0000	1.0000	0.9533	1.0000	0.9479	1.0000	1.0000	1.0000	1.0000
S11	1.0000	1.0000	1.0000	1.0000	1.0000	0.5203	0.5856	0.5038	0.7325	0.5528	1.0000	0.9209
S12	1.0000	1.0000	1.0000	1.0000	1.0000	0.6001	0.6621	0.5860	0.8085	0.6358	1.0000	1.0000

Table 24, FAHP: The achieved amounts of S_k

Using equation 17 and equation 18, the weights of the criteria and the vector of the weights is calculated as follows:

Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	$V(M_i \geq M_j, \dots, M_k)$	$W' (x_i)$	w_i
	min S1 $\succcurlyeq$ S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12	0.0000	0.0000
	min S2 $\succcurlyeq$ S1, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12	0.0000	0.0000
	min S3 $\succcurlyeq$ S1, S2, S4, S5, S6, S7, S8, S9, S10, S11, S12	0.0000	0.0000
	min S4 $\succcurlyeq$ S1, S2, S3, S5, S6, S7, S8, S9, S10, S11, S12	0.0000	0.0000
	min S5 $\succcurlyeq$ S1, S2, S3, S4, S6, S7, S8, S9, S10, S11, S12	0.2172	0.0362
	min S6 $\succcurlyeq$ S1, S2, S3, S4, S5, S7, S8, S9, S10, S11, S12	0.9957	0.1659
	min S7 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S8, S9, S10, S11, S12	0.9496	0.1582
	min S8 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S7, S9, S10, S11, S12	1.0000	0.1666
	min S9 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S7, S8, S10, S11, S12	0.8029	0.1337
	min S10 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S7, S8, S9, S11, S12	0.9479	0.1579
	min S11 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S12	0.5038	0.0839
	min S12 $\succcurlyeq$ S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11	0.5860	0.0976

Table 25, FAHP: Calculation of the weights of the criteria

Vector of weight, w' (x_i), and Vector of normalised attributes, w_i												
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2
$w' (x_i)$	0.0000	0.0000	0.0000	0.0000	0.2172	0.9957	0.9496	1.0000	0.8029	0.9479	0.5038	0.5860
w_i	0.0000	0.0000	0.0000	0.0000	0.0362	0.1659	0.1582	0.1666	0.1337	0.1579	0.0839	0.0976

Table 26, FAHP: Vector of the weights of the criteria

Tables 27 to 33 show the way in which the same calculations take place with regards to criterion a_1 of this study. The step by step calculation of the remaining criteria, i.e. a_2 to d_2 , is shown in section 10.1.4 of appendix I.

Migration through the caprock (a_1)				
	A	B	C	D
A	(1,1,1)	(6,7,8)	(7,8,9)	(7,8,9)
B	(1/8,1/7,1/6)	(1,1,1)	(1,1,1)	(1,1,1)
C	(1/7,1/8,1/9)	(1,1,1)	(1,1,1)	(1,1,1)
D	(1/7,1/8,1/9)	(1,1,1)	(1,1,1)	(1,1,1)

Table 27, Fuzzy pair-wise comparison matrix for criteria a_1

TFNs		Sum of Rows				Sum	Inverse	S_k	
A	1	1.00	6.00	8.00	7.00	22.00	31.35	0.0274465	0.60382
	2	1.00	7.00	9.00	8.00	25.00	34.38	0.0290875	0.72719
	3	1.00	8.00	9.00	9.00	27.00	36.43	0.0319007	0.86132
B	1	0.13	1.00	1.00	1.00	3.13		0.0274465	0.08577
	2	0.14	1.00	1.00	1.00	3.14		0.0290875	0.09142
	3	0.17	1.00	1.00	1.00	3.17		0.0319007	0.10102
C	1	0.11	1.00	1.00	1.00	3.11		0.0274465	0.08539
	2	0.11	1.00	1.00	1.00	3.11		0.0290875	0.09049
	3	0.13	1.00	1.00	1.00	3.13		0.0319007	0.09969
D	1	0.11	1.00	1.00	1.00	3.11		0.0274465	0.08539
	2	0.13	1.00	1.00	1.00	3.13		0.0290875	0.09090
	3	0.14	1.00	1.00	1.00	3.14		0.0319007	0.10026

Table 28, Showing the achieved TFNs for S_k s of criteria a_1

S_k			
	l	m	u
S1	0.6038	0.7272	0.8613
S2	0.0858	0.0914	0.1010
S3	0.0854	0.0905	0.0997
S4	0.0854	0.0909	0.1003

Table 29, TFN values of S_k for each alternative with respect to criteria a_1

s1 >= s2	1	s3 >= s1	0
s1 >= s3	1	s3 >= s2	0.937787
s1 >= s4	1	s3 >= s4	1
s2 >= s1	0	s4 >= s1	0
s2 >= s3	1	s4 >= s2	0.965391
s2 >= s4	1	s4 >= s3	1

Table 30, Degree of possibility of different amounts of S_k for TFNs with respect to a_1

	S1	S2	S3	S4
S1	1.0000	1.0000	1.0000	1.0000
S2	0.0000	1.0000	1.0000	1.0000
S3	0.0000	0.9378	1.0000	1.0000
S4	0.0000	0.9654	1.0000	1.0000

Table 31, The achieved amounts of S_k for criteria a_1

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	1.0000	1
	min S2 >= S1, S3, S4	0.0000	0
	min S3 >= S1, S2, S4	0.0000	0
	min S4 >= S1, S2, S3	0.0000	0

Table 32, Calculation of the weights of the alternatives with respect to criteria a_1

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (xi)	1.0000	0.0000	0.0000	0.0000
wi	1.0000	0.0000	0.0000	0.0000

Table 33, Vector of the weights of the alternatives with respect to criteria a_1

Tables 34, 35 and 36 show the final weight of criteria and alternatives that have been obtained and the final ranking of the risks associated with CO₂ storage underground as a result of using the FAHP method.

c	0.0000	0.0000	0.0000	0.0000	0.0362	0.1659	0.1582	0.1666	0.1337	0.1579	0.0839	0.0976
A	1.0000	0.8507	0.6625	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B	0.0000	0.0000	0.3375	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C	0.0000	0.0837	0.0000	0.0000	0.0000	0.5659	0.7931	0.6497	0.5360	0.6055	0.0908	0.0000
D	0.0000	0.0656	0.0000	0.0000	0.0000	0.4341	0.2069	0.3503	0.4640	0.3945	0.9092	1.0000

Table 34, Weights of the criteria and alternatives using FAHP

Risk ranking of the alternatives	
A	0.036174315
B	0
C	0.502447843
D	0.461377843

Table 35, Weight of the alternatives with respect to the criteria using FAHP

Risk ranking of the alternatives	Rank
Percolation of CO ₂ through the caprock (A)	3
Migration of CO ₂ along a fracture or permeable zone (B)	4
Leakage of CO ₂ through or along the injection well (C)	1
Leakage of CO ₂ through other wells (D)	2

Table 36, Final weight of the risk elements using the FAHP method

CHAPTER 7

ANALYSIS AND DISCUSSION

7 ANALYSIS AND DISCUSSION

7.1 Introduction

This chapter analyses the results obtained as a result of the risk modelling conducted during the course of this study followed by the ways in which the modelling approach of this study can potentially play a significant role in analysing and estimating the risks associated with underground storage of CO₂ in future as well as current projects.

The following is the way in which the European Commission currently performs risk analysis and risk management for geological storage of CO₂ and therefore recommends the CCS industry to do so too. The EU Commission in its Guidance Document 1 (GD1)⁷ recognises that the current level of knowledge with respect to the risk analysis of CO₂ storage sites is limited and as a result states that: “the overall approach is to identify and mitigate any significant risks; The CA should recognise that operators must undertake site-specific approaches in their risk assessment and management (European Parliament, 2011a).”

However, in order to provide a benchmark and a basis for risk analysis and risk management for the storage site operators and the insurance industry, the EU Commission makes use of the approach used in the CO2QUALSTORE report⁸ which has been adapted in accordance with the needs of the CCS Directive.

According to the CCS Directive, CO₂ storage sites should only be selected, used and operated where there is no significant risk of leakage and that the stored CO₂ should be permanently contained (European Commission, 2009). Significant risk is defined in the CCS Directive’s Article 3(18) as meaning “a combination of probability occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of the Directive as far as the storage site is concerned” (European Commission, 2009).

⁷ EUROPEAN PARLIMENT 2011a. Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide Guidance Document 1 (GD1): CO₂ Storage Life Cycle Risk Management Framework. *In*: COMMISSION, E. (ed.). Official Journal of the European Union: European Commission.

⁸ DET NORSKE VERITAS (DNV) 2010. CO2QUALSTORE Report - Guideline for Selection, Characterization and Qualification of Sites and Projects for Geological Storage of CO₂.

Therefore, according to the CCS Directive, the risks have to be analysed and determined as to how significant they are and if deemed significant, to what extent do they need to be addressed by storage site operators and considered by the insurance industry when insuring CO₂ storage sites.

7.2 Risk Analysis Methods Proposed by the European Commission in Guidance Documents 1 and 4

As mentioned in section 7.1, the CCS Directive makes use of a modified version of risk assessment and risk management technique used by the CO₂QUALSTORE report in order to perform risk assessment for the lifecycle of CO₂ storage sites in general.

The proposed risk analysis and risk management approach used in the CCS Directive is divided into three steps, Overall Risk Management Process, Interaction between Operator and Competent Authorities and Risk Management at different project phases.

The following framework has then been provided for the overall risk management process in geological storage of CO₂ (European Commission, 2009):

- Risk identification and assessment
- Risk ranking
- Risk management measures

Risk identification and assessment entails the identification, assessment and characterisation of potential hazards and risks towards the containment of CO₂ in underground storage sites, exposure and effects assessment (European Parliament, 2011a).

Furthermore, risk ranking means to rank and categorise the identified risks and hazards based on a standard matrix of probability and severity of outcome (see Figure 22). This step consists of two options: Significant or Insignificant. The next step is to describe and evaluate preventive and corrective measures that can be used to manage the risks (Det Norske Veritas (DNV), 2010).

The EU Commission recognises and mentions in GD1 that while its risk analysis framework is based on a modified version of the CO2QUALSTORE guideline, operators can also use other risk analysis and risk management methods, as long as they comply with the requirements of the CCS Directive.

7.2.1 EU Commission Guidance Document 1 (GD1) Risk Ranking Mechanism

As mentioned before, risk ranking is one of the most important elements in risk analysis since it enables the storage facilities' operators to be able to identify which risks are significant and which ones are insignificant. In addition, this also enables insurance companies to assess the risks of CO₂ storage more effectively at any given storage facility and therefore devise insurance policies that are more in favour of the CCS industry.

The EU Commission's CCS GD1 already provides a risk ranking mechanism that can be used by the CCS industry. This mechanism is described below.

The proposed method for ranking the risks associated with CO₂ storage is to categorise the risks using a standard matrix of probability and impact/severity of occurrence (shown in figure 22).

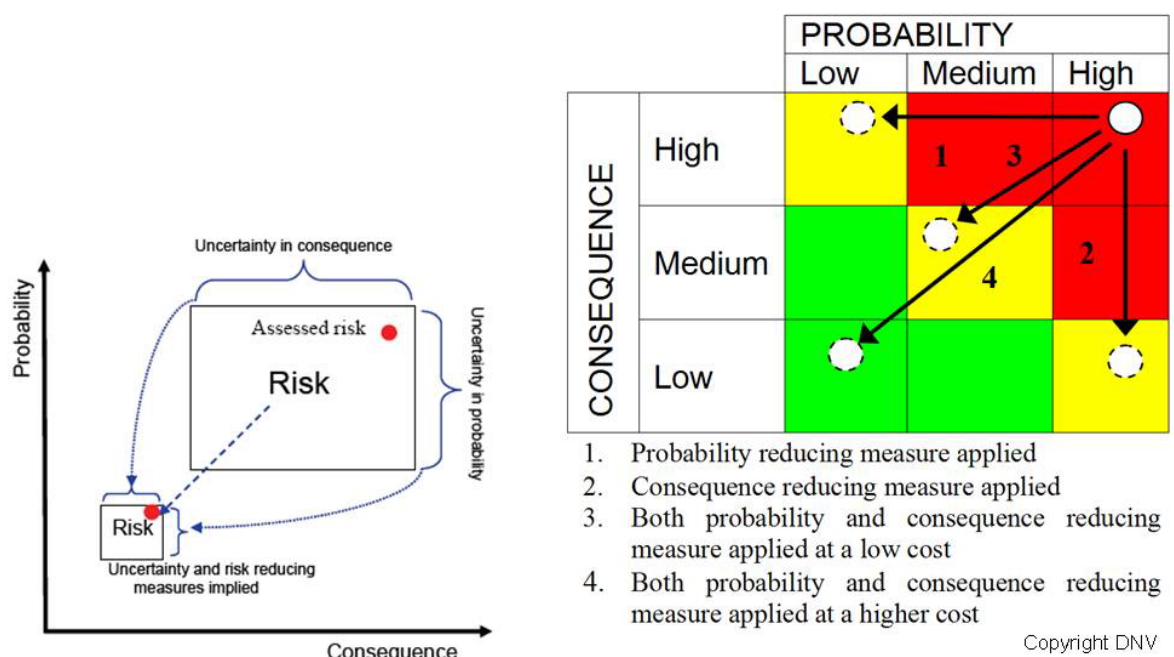


Figure 22, Risk Management Framework used in CCS GD1 (Det Norske Veritas (DNV), 2010)

The initial ranking, based on the risk identification stage, may be supported by the analysis carried out in the risk assessment step. The aim of this process is to characterize the potential significance of each risk along with its probability of occurrence and consequences should it occur. The relative significance of each risk should then be characterized, prioritised and placed in either the significant or insignificant categories. GD1 describes insignificant risks as “ones that are broadly regarded as not posing a significant danger to human health or environment” (European Parliament, 2011b). Furthermore, it describes significant risks as “ones that must be reduced to insignificant through implementation of risk reducing measures in order to gain project approval, or to meet anticipated conditions for site closure (European Parliament, 2011b).

In general, it is recommended by the GD1 that in order to avoid disappointment, the ranking takes place conservatively owing to the fact that there is a high level of uncertainty with regards to the probability of leakage and the likelihood effects that a potential leakage may entail. Furthermore, the pessimistic end of severity and probability of occurrence scale have to be taken into account in order to ensure avoidable leakages of CO₂ from the storage reservoirs do not occur.

On the other hand however, one has to make sure that they avoid being biased when analysing and assessing the risks. Moreover, the risks have to be managed and downgraded effectively as more knowledge about particular CO₂ storage sites becomes available and uncertainties are reduced.

7.3 Addressing Risks in EU Commission Guidance Document 4 (GD4)

As mentioned in section 3.4.3 of this thesis, by virtue of the inclusion of geological storage sites under Annex I of the Emissions Trading Directive, installations will be required to surrender allowances for any emissions from the site (including leakage) as calculated pursuant to the Monitoring and Reporting Guidelines for CCS. The amount of the Financial Security for this obligation can be based on the potential total tons of emissions, including due to leakage(s), multiplied by the market cost of purchasing an equivalent amount of allowances. This calculation will require estimates for the total tons of emissions that may be

released (including due to leakage(s)), the timing of emissions, and cost of allowances when releases occur.

It is worth noting that European Commission's GD4 has exercised language that specifically did not recommend the determination of FS (for the surrender of allowances due to leakages) by multiplying the estimated amount of funds by the probability that the scenario occurs. Now, a "realistic and appropriate middle ground scenario taking into account of all available evidence of the site-specific risk profile is used" is recommended. In addition, GD4 contains a method for the "calculation of the potential leakage amount based on a probability distribution of the amount of leakage from the storage complex" where "there is a proposed use of probability distribution for determining the size of a leakage (not the probability that it will occur)". Furthermore, it gives regulators the choice of choosing a risk percentile for the size of the leakage to be used instead as an estimate, instead of an inflexible 25% default contingency for FS. Furthermore, there is specific mention of the fact that FS amounts may now be updated "in case of leakage or significant irregularities, or where the monitoring plan is updated pursuant to Annex II of the CCS Directive". For example, in the UK, the Environment Agency adds a contingency of about 40-50% in determining the minimum amount of the FS for transfrontier movements of hazardous waste (European Parliament, 2011d). Owing to the fact that there is little experience in the field of geological storage of CO₂, GD4 suggests for the storage site operators to estimate the said amount of FS based on the following:

- A conservative estimate of the maximum portion of CO₂ that can be leaked from storage sites, which in most scenarios would be less than 100%;
- A calculation of the potential leakage amount based on a probability distribution of the amount of leakage from the storage site taking into account the geological characteristics of the site, facility design, monitoring programme and statistical modelling (European Parliament, 2011d).

7.3.1 An Industry View of EU Commission CCS Guidance Document 4 (GD4)

Financial Security and Contribution Articles are of particular concern. Guidance interpreted as requiring uncapped, uncertain liability which would be a major barrier to industry

participation. Provision of security for worst case scenario as well as 25% contingency would make operator risk entirely disproportionate especially as the Competent Authority would have already assessed the operator as being fit and proper as well as commented on the suitability of the proposed storage site as part of the permitting process. They propose required security and additional contingency measures to be assessed on a site-by-site basis. Also highlighted is the need to distinguish liabilities between the demonstration and commercialization phases as demonstration projects will be facing first-of-a-kind issues.

Probabilistic risk management is already being used in evaluating energy sector technologies by both industry and government. Furthermore, any risk to the CA would be spread to many storage sites, therefore having a financial security based on worst case scenario for each storage site is disproportionate to the risk. Alternatively, arrangements can be made that would take into account risk exposure and each storage site operator would pay a risk adjusted payment based on storage site assessment. Money would go into a central fund held by CA.

Propose that if Member State has issued a permit to the operator, assume that there is very low risk of that site leaking (issues of oil wells past and access to information is made public).

Inclusion of storage sites within ETS exposes storage site operator to further significant financial risk. In the event of leakage, submit allowances for CO₂ leaked. However, the ability of operator to hedge the exposure to allowance price volatility is significantly limited. A reasonable suggested compromise would be for the operator and the competent authority to agree to a shared risk profile, perhaps through an insurance mechanism which would allow risk exposure to be capped for operator. Examples of this can be seen in current proposals in the UK for capping risk of nuclear risk management where the CA is proposing the fixing of a fee in advance that includes a risk premium, but ultimately caps the exposure for operators. As currently drafted, GD4 could require the operator to make an accounting provision equivalent to value of stored CO₂. This would be a significant uncertain liability for the operator and would discourage investment. Furthermore, the financial strength of operator should be taken into account when agreeing an acceptable method such that greater financial strength should provide greater latitude to the operator.

7.4 Proposed Risk Analysis Mechanism

The risk ranking section within the risk analysis method used in GD1 will not be able to act as the optimum solution in real life CCS projects since its outcome only states whether a risk is significant or insignificant. On the other hand, not only the risk ranking techniques used in this project enable CCS stakeholders to assess the significance of risks, they also enable them to determine the extent to which the risks are significant or insignificant in comparison to each other. Therefore, the techniques use in this thesis enable storage site operators to assess the probability of occurrence of risks having studied the significance of them in comparison to each other and decide accordingly. In other words, CCS GD1 is only able to determine storage site operators' decisions based on absolute values, i.e. significant or insignificant. On the other hand however, the techniques used in this research assist storage site operators in decision making when it comes to dealing with uncertainty and choosing the optimum decision. Moreover, the proposed methods work in conjunction with each other in order to calculate the significance and likelihood of occurrence of the risks of leakage or hazards that may prevent complete and permanent containment of CO₂ in storage reservoirs in comparison with each other. After this, it is the storage site operators' responsibility to make decisions based on the specific location of the storage site, local population density, the nature of the biosphere, atmospheric dispersal and whether the site is onshore or offshore (European Parliament, 2011c). The composition of the CO₂ stream should also be taken into consideration (see Chapter 3 of EU Commission's Guidance Document 2 (GD2) for more discussion)⁹.

The GD1 recommends making use of focus groups and brainstorming sessions amongst a group of participants in order to assess the probability, likelihood and potential impact of the risks. It further states that, in order to avoid bias, the participants should be chosen from experts that have detailed knowledge of the particular CCS project in question as well as participants who are not viewed as experts in the CCS technology. This is sensible.

Hence, similar to the GD1 risk assessment method, this research project also makes use of expert opinion in order to perform the risk analysis techniques. However, this project has

⁹ EUROPEAN PARLIMENT 2011b. Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide Guidance Document 2 (GD2): Characterisation of the Storage Complex, CO₂ Stream Composition, Monitoring and Corrective Measures. *In*: COMMISSION, E. (ed.). European Commission,.

only relied upon opinions of national and international experts in the field of geological storage of CO₂. Equally, it has mathematically devised a risk rating system that also takes into account uncertainty by performing sensitivity analysis.

The AHP and FAHP techniques were used in this research in order to analyse the importance and criticality of the risks associated with the storage of CO₂ in underground storage reservoirs. The said techniques produced a series of rankings for the risks shown in figure 7 of section 4.3, the results of which can be seen in table 37.

The AHP method was used since it is a useful and effective way to prioritise between a set of alternatives taking into account certain criteria in addition to its sophisticated but yet relatively easy nature.

Moreover, the FAHP method was used in order to overcome the fact that human judgements are commonly imprecise, subjective and ambiguous, by calculating the importance and criticality of the risks associated with CO₂ storage through fuzzifying the pair-wise comparison matrices that were used as part of the AHP method. The results of which can be seen in table 37.

Alternatives	AHP	FAHP
Percolation of CO₂ through the caprock	0.125	0.036
Migration of CO₂ along a fracture or permeable zone	0.108	0
Leakage of CO₂ through or along the injection well	0.378	0.502
Leakage of CO₂ through other wells	0.389	0.461

Table 37, Calculated results using the AHP and FAHP methods

As seen in table 37, the AHP and FAHP methods produced very similar results. Furthermore, using the AHP method resulted in the following ranking. The “leakage of CO₂ through other wells” was ranked first, “leakage of CO₂ through or along the injection well” was ranked second, “percolation of CO₂ through the caprock” was ranked third and finally the “migration of CO₂ along a fracture or permeable zone” was ranked as the least important risk associated with CO₂ storage. On the other hand, results of the FAHP method suggests “Leakage of CO₂

through or along the injection well” is ranked above the “Leakage of CO₂ through other wells” in terms of importance, criticality and likelihood of occurrence.

As shown in figure 23, this suggests that these two risks are as important as each other and have to be taken into account equally when storage site operators and insurance companies are analysing the risks of CO₂ leakage from storage sites.

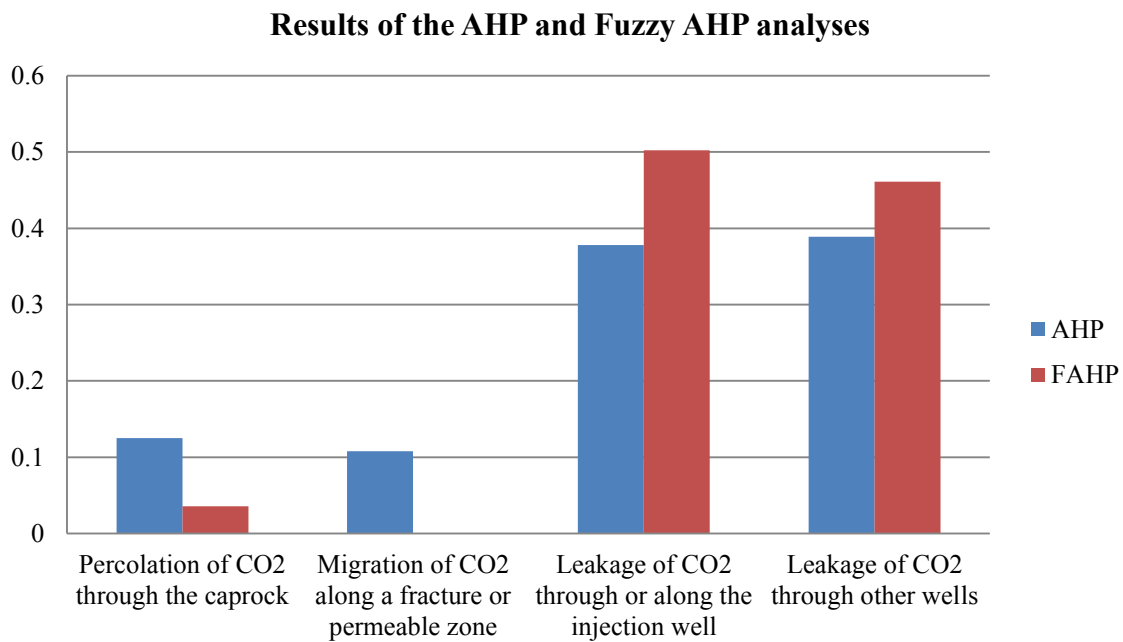


Figure 23, Comparison of results of the AHP and FAHP methods

In order to test the robustness of the AHP and AHP Fuzzy methods used in this research and to see whether or not the obtained ranking of the risks would change when different methods are used, two other systems engineering optimisation techniques were used, TOPSIS and PROMETHEE. What follows is a short description of the nature of the said two methods and the way in which they operate in order to achieve the same outcome to the AHP technique whilst using other methodologies. The methodologies associated with TOPSIS and PROMETHEE methods and the ways in which their respective calculations took place are shown in sections 10.1.1 and 10.1.2 of Appendix I respectively.

7.4.1 *Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)*

TOPSIS is a multi-criteria decision making method developed by Hwang and Yoon in 1981 which is used on a large scale (Hwang and Yoon, 1981). The method was further developed by Yoon in 1987 (Yoon, 1987) and Hwang, Lai and Liu in 1993 (Hwang et al., 1993).

Gumus describes TOPSIS as an approach for dealing with complex systems related to making a preferred choice amongst several alternatives and which provides a comparison of the considered options (Gumus, 2009). TOPSIS is based on a simple and intuitive concept; it enables consistent and systematic criteria, which is based on choosing the best alternative having the shortest distance from the positive ideal solution and the furthest distance from the negative ideal solution (Joshi et al., 2011).

TOPSIS is a goal based decision-making technique. This method evaluates each of the given options and using quantitative information determines which one may be closest to which has been identified as the goal or the overall preferred option. So what one is looking at is – using the nominal design information – which individual alternative is closest to the ideal solution that a project at any given stage would require or prefer. Furthermore, one of the advantages of using TOPSIS is its ability to identify the best alternative out of a set of alternatives quickly (Parkan and Wu, 1997).

The TOPSIS method has been deployed in order to calculate and obtain the ideal solution. Moreover, the ideal solution in TOPSIS is one which has the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution. Furthermore, in the case of the CO₂ storage technology, the negative ideal solution would be the leakage of CO₂ from underground storage reservoirs and the positive ideal solution would be containment of CO₂ underground.

In order to be able to choose the preferred solution from a set of alternatives using the TOPSIS method, one has to go through five steps which have been described in detail in section 10.1.1 of Appendix I.

7.4.2 Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)

The PROMETHEE method is based on mathematics and sociology. Furthermore, this method was developed and presented by J.P. Brans in 1982 at a conference and it has been developed and refined since then (Brans, 1982). This technique is considered to belong to the partial aggregation methods – some also call them outranking methods – and was partly designed as a reaction to the complete aggregation (MAUT) methods (Bekiaris and Nakanishi, 2004).

The PROMETHEE method has been used extensively in a wide range of topics ranging from Environmental Management, Hydrology and Water Management, Business and Financial Management, Chemistry, Logistics and Transportation, Energy Management to Medicine, Agriculture and Education.

This technique, which is a type multi-criteria decision making technique, helps decision makers find an alternative solution that best suits their respective projects as oppose to providing them with one solution. One of the main advantages of this technique is that it can be used when the important elements of the decision are difficult to quantify or compare.

In a recent research project undertaken by Behzadian and colleagues, it was discovered that Environmental Management was the most popular topic which uses the PROMETHEE methods and it's applications (Behzadian et al., 2010). Furthermore, within the environmental management area, the topics that were covered were, Waste Management, LCA, EIA and Land-Use Planning.

The requirements for the PROMETHEE method to be carried out and subsequently determine the preference structure of the decision makers are:

- Relative importance of the criteria that is being considered. This has also been referred to as the “relative weight of the criteria” in section 10.1.2 of the thesis;
- Participants’ preference function, which he/she uses when comparing the contribution of the alternatives in terms of each separate criterion (Macharis et al., 2004).

Nijkamp et al. and Eckenrode developed different methods that can be used in order to determine the relative weights of the criteria for the use of the PROMETHEE method (see (Nijkamp et al., 1990) and (Eckenrode, 1965) for an overview of these methods). According

to a recent study by Macharis and colleagues, PROMETHEE does not provide any guidelines on the calculation of the relative weights (Macharis et al., 2004). Furthermore, in this regard, the assumption of this technique is that the decision-maker is able to weigh the criteria appropriately, at least when the number of criteria is not too large. Moreover, she proposes that for large amounts of data, the relative weights can be calculated using methods such as: direct rating, point allocation, trade-off, pair-wise comparisons, and so on (Macharis et al., 2004). For the purpose of this research project, the pair-wise comparison method i.e. the AHP method has been chosen in order to provide the input parameters i.e. the relative weights of the criteria for the PROMETHEE method. This was owing to the fact that as described in chapter 5, as part of the AHP method, an expert survey was sent to experts within the field of geological storage of CO₂ underground. Furthermore, the results from the survey provided the input parameters for the AHP method which in turn can also be used for the PROMETHEE method. With this information, an overall preference index $\pi(k,l)$ can be calculated, taking all the criteria into account. This preference index is based on the positive preference flow (Φ^+) and negative preference flow (Φ^-) for each alternative, which measures how an alternative may outrank or be outranked by the other alternatives. The net preference flow (Φ^{net}) is calculated by subtracting the negative preference flow from the positive reference flow. As a result, the most desired solution can be chosen as the one with the highest net preference flow.

The way in which the negative, positive and the net preference flows can be calculated using the data generated by the AHP method, has been described in full in section 10.1.2 of Appendix I.

According to tables 38 and 39, the AHP, TOPSIS and PROMETHEE methods all produced the same ranking for the risks shown in figure 7. The “leakage of CO₂ through other wells” was ranked first, “leakage of CO₂ through or along the injection well” was ranked second, “percolation of CO₂ through the caprock” was ranked third and finally the “migration of CO₂ along a fracture or permeable zone” was ranked as the least important risk associated with CO₂ storage. Therefore, it was concluded that the AHP method is a useful and robust method in analysing the risks associated with the underground storage of CO₂.

Having looked at the quantitative outputs shown in table 38, it was realized that the performance values are such that establishing a solid rank between some alternatives is

challenging as simple changes in the input information can potentially change the rankings. For example, the performance values of “Leakage of CO₂ through or along the injection well” and “Leakage of CO₂ through other wells” were very close to each other which can be shown by undertaking sensitivity analysis. Therefore, the said matter was another reason for using the Fuzzy AHP method in this research in order to inspect whether or not the results of the AHP method would vary with little variation in the input parameters.

Furthermore, using the Fuzzy version of the AHP method, it was inspected that the order of importance and significance of the said two risk elements changed. Figure 23 further illustrates this matter by showing that the said two alternatives are not that different in performance. This is why the FAHP results are slightly different to the AHP results.

Therefore, it is concluded that “Leakage of CO₂ through the injection well” and “Leakage of CO₂ through other wells” are more important than other risks. However, it is difficult to say with certainty as to which one of the said two risks are more important in comparison to one another. Therefore, it was further concluded that the said two risks is potentially as important as each other and have to be taken into account equally when analysing the risk of leakage associated with CO₂ storage.

Alternatives	AHP	TOPSIS	PROMEHTEE	FAHP
Percolation of CO ₂ through the caprock	0.125	0.203	-0.249	0.036
Migration of CO ₂ along a fracture or permeable zone	0.108	0.116	-0.302	0
Leakage of CO ₂ through or along the injection well	0.378	0.67	0.261	0.502
Leakage of CO ₂ through other wells	0.389	0.676	0.289	0.461

Table 38, Numerical value that each MCDM method calculated for the risks associated with CO₂ storage.

Alternatives	Rank			
	AHP	TOPSIS	PROMEHTEE	FAHP
Percolation of CO ₂ through the caprock	3	3	3	3
Migration of CO ₂ along a fracture or permeable zone	4	4	4	4
Leakage of CO ₂ through or along the injection well	2	2	2	1
Leakage of CO ₂ through other wells	1	1	1	2

Table 39, Ranking of risks of CO₂ storage using different MCDM methods

Results of the AHP, TOPSIS, PROMETHEE and Fuzzy AHP Analyses

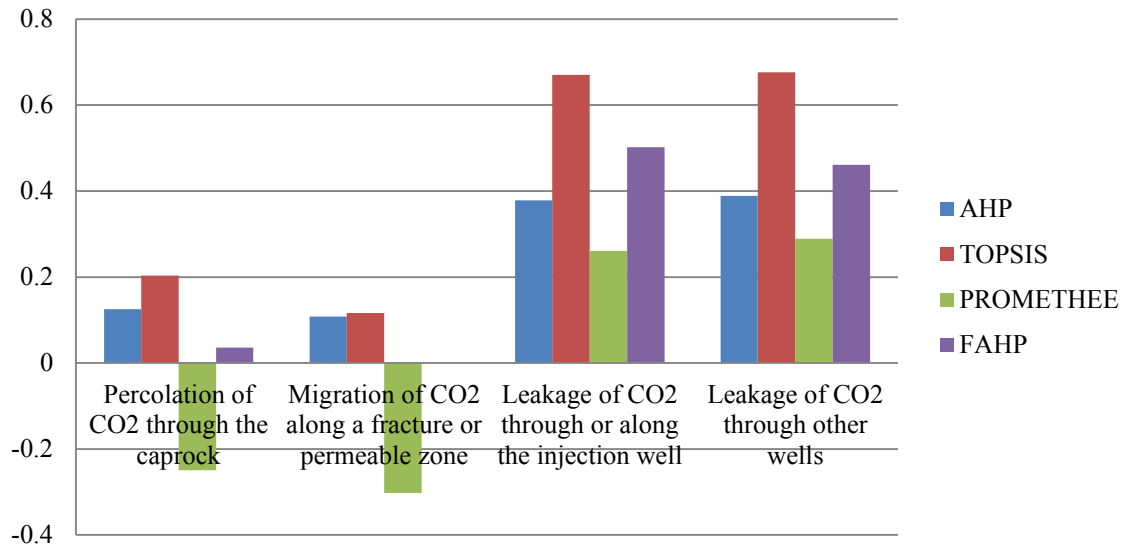


Figure 24, Comparison of results of AHP, TOPSIS, PROMETHEE and FAHP methods

MCDM methods are generally used in order to find the optimum solution from a range of suitable solutions in a multi-criteria decision-making problem. Emphasis is placed on the word “optimum”. Many solutions can be suitable but not all can be optimum. The AHP, TOPSIS and PROMETHEE methods point out the optimum solution for the decision makers rather than prescribing the correct one depending on their needs in any given project.

Since the four MCDM methods used in this project each have a different notion of optimality, therefore, the optimum solution obtained as a result of carrying out each method is also different. However, what is important is that a preference table has now been constructed as a result of carrying out said techniques. Therefore, in case for any reason, the decision makers are not able to choose the best alternative, they can choose the second best alternative according to their specific needs. The same principle can be applied to the case of the risks associated with storage of CO₂ underground.

Amongst many different MCDM methods, four were employed in order to investigate the significance and criticality of certain risks in this study and their contribution towards the ultimate risk at the top of the fault tree which was “leakage of CO₂ to the through the caprock”.

As mentioned above, as the notion of optimality is different in different MCDM methods, it was expected that the analysis from different methods would yield dissimilar results. Therefore, it was decided that more than one MCDM method would be used in order to obtain a more robust result. However, since the AHP, TOPSIS and PROMETHEE methods calculated the same ranking for the risks, their reciprocal findings suggest that the said methods are suitable techniques in analysing risks associated with CO₂ storage in terms of their importance and criticality in comparison to each other. Furthermore, having performed sensitivity analysis using the Fuzzy AHP method and obtaining very similar results for the ranking of risks, it can be also concluded that the methods used in this thesis are robust methods.

In conclusion, such risk analysis methods enable the storage site operators to focus on the weak points within the storage site, rank them in accordance to their importance and criticality towards the leakage of CO₂, evaluate how these weak points can be properly tested and addressed if need be. Furthermore, this will enable the insurance industry and regulators to understand the risks associated with this industry as a whole more effectively and insure and regulate the storage sites more to the benefit of the CCS industry in order to encourage the growth and implementation of this technology.

CHAPTER 8

CONCLUSIONS

8 CONCLUSIONS

The IPCC Working Group III (IPCC WC III) published their contribution to the IPCC Fifth Assessment Report (AR5) in April 2014 and within the report there was a strong emphasis on the CCS technology in order to achieve the ambitious GHG emissions reduction targets. The two most important points within the report were the following:

- Most climate change mitigation models show that without CCS (or even a considerable delay), the world will fail to limit atmospheric emissions of CO₂ to 450ppm (IPCC, 2014);
- Without CCS, the total cost of limiting CO₂ emissions to 450ppm could increase by 138% (Darby, 2014).

The IPCC WG III further states that CCS could be seen in the market providing that it is incentivised by regulation and be compensated by sufficiently high carbon prices or direct financial support should additional investment be needed caused by factors such as a reduction in plant efficiency (IPCC, 2014).

Barriers to commercial scale deployment of the CCS technology include concerns about plant safety during operation phase, risks associated with the transportation of CO₂ and perhaps more importantly, the long-term liability of storage sites in case leakages occur subsequent to end of injection and storage reservoirs have been sealed off. Storage site operators therefore have to ensure that the integrity of CO₂ wells are assessed effectively in order to minimise the probability of occurrence of risks and their potential consequences that may be caused as a result of pressure build-up in the reservoirs.

As mentioned in the IPCC 2014 report, in order for the large scale deployment of CCS technology to be successful, the support of regulators and insurers is necessary. This is owing to the fact that the companies adopting this technology will in this case be able to share the liability and therefore be compensated should leakage occur. Furthermore, insurance companies have to be able to estimate the risks associated with CO₂ storage appropriately in order to feel content and as a result insure CO₂ storage sites.

A review of the most recent regulatory and legislative literature was conducted in order to inspect the ways in which the risks of leakage and long-term liability are currently addressed in CCS related literature. Therefore, in chapter 3, this research has analysed and hence developed an understanding of the latest regulatory and legislative developments within the CCS industry. This was done by studying specific risk-related financial and regulatory issues with regards to CCS as well as the ways in which regulatory and legislative aspects of CCS are addressed in competing jurisdictions and the lessons that should be learnt from them. Furthermore, chapter 3 also compares the oil and gas, nuclear and waste management industries with the CCS industry with regards to their risk profiles and the ways in which those risks are addressed along with the different methods that they make use of in order to obtain insurance against the respective risks.

As it stands, CCS legislation is comprised of an overlapping network of international agreements and regional policies in which they all form a strong basis for environmental protection in case potential leakages of CO₂ from storage sites occur. This is done through the use of the precautionary and polluter pays principles. However, these legislative instruments form an uncoordinated legal basis for CCS with overly stringent liability provisions posing a significant barrier to stakeholder investment, technological development and future roll-out of commercial scale CCS projects.

CCS will be unfolded in a competitive energy sector and holds within it ramifications for energy security. However, the current overly guarded regulation frameworks, particularly at the EU level, are restrictive to CCS competition. Therefore, the UK Government is advised to work with industry in providing clear regulatory solutions for a predictable investment framework for CCS when transposing the EU CCS Directive. This would allow for the tailoring of UK transposition legislation, having in mind the international legal basis for CCS, to the specific investment and regulatory climate of the UK. Furthermore, it would take advantage of pre-existing good relationships between policymakers and industry which can lead to invaluable feedback on the appropriateness and consequences of regulatory decisions. Ultimately, it is suggested that this would enhance the precision of monitoring activities and allow for a more inclusive approach to risk management measures.

Real-world examples of flexible approaches to CCS regulation can be seen in the case of Norway, Australia, Canada, Germany, Netherlands and the USA. Moreover, Norway has incentivised CCS by legislating a carbon emissions tax of €40 t/CO₂. Furthermore, CCS is

regulated both under the Norwegian Pollution Act and the Petroleum Act, however, at the present, responsibility for leakages is not satisfactorily regulated under Norwegian law. In the case of Australia, long term liability associated with the storage of CO₂ is covered under the Research Development and Demonstration approval provision under the Victorian Environment Protection Act, which recognises that more comprehensive legislative cover would be necessary in the future for any commercial geo-sequestration projects. Moreover, in Canada, the CCS Act enables the Government to issue closure certificates which in effect transfers the responsibility for the stored CO₂ from the storage site operator to the Government.

In the US, the EPA has proposed a default 50-year time-frame for CCS liability with the provision that the acting EPA Director may shorten or lengthen that period based on risk data gathered during the permitting process. Additionally, this new permitting system will allow for financial guarantees for CCS to be chosen from a variety of different options which would allow for greater market competition and rapid deployment of lower-cost solutions in the CCS industry. Netherlands plans to implement the CCS Directive by amending the Netherlands Mining Act, which means that liability will lie with the storage license holder, up to the point of the license expiration.

In addition, Germany has indicated that it will adopt a draft act on CCS which could potentially include the possibility that after a period of 30 years from the decommissioning of a plant, and thus about 80 years after its start-up, operators may transfer their responsibility to the Federal Government (once the operator has established proof of the long-term safety of the storage site). Notably, the CCS Demonstration Project Network which is sponsored by the European Commission has also expressed the belief that long-term CCS liability will be dealt with in the manner of oil spills – with “the state assuming liability after a regulated abandonment process”.

As a result of said analyses (and reflecting initial work on the subject pertaining to the draft GD4), it was concluded that the EU GD4 demonstrates the knowledge that a risk-sharing approach, such as commercial insurance or risk pooling, would be preferable. However, since they perceive that CCS technology is not well developed and lacks a long empirical history, they posit that a risk-sharing approach would create a high degree of uncertainty in estimating probability and magnitudes of potential leakages. In addition, provision of security for worst case scenario as well as 25% contingency would make operator risk entirely disproportionate

especially as the CA would have already assessed the operator as being fit and proper as well as commented on the suitability of the proposed storage sit as part of the permitting process.

Additionally, the proposed risk analysis method used in the EU GD1 will not be able to act as an optimum method when stakeholders are required to assess the risks of CO₂ storage since it provides only two possible outcomes, significant or insignificant. On the other hand, this research project has developed a risk analysis mechanism which enables the stakeholders to assess the extent to which a potential risk is significant or insignificant.

Moreover, this research project's aim was to develop a novel mechanism by which the insurance industry would be able to assess the risks associated with the storage of CO₂ under geological formations more effectively and therefore adjust their premium rates when insuring for CCS projects. In addition, this project's results will also be beneficial for the regulators in enabling them to regulate and plan more effectively in order to incentivise stakeholder participation and investment in the CCS technology.

As part of carrying out the said mechanism, an expert survey was designed and presented to national and international CO₂ storage experts within academic institutions and companies that were active in this field. The output of the expert surveys were then used as input parameters for three different systems engineering optimisation modelling techniques that mathematically calculated the significance of each risk in comparison to other risks from different points of views. Furthermore, in order to account for possible subjectivity and ambiguity associated with the experts' opinion, Fuzzy Logic was used in order to perform sensitivity analysis and assess whether or not the result of the said analyses would differ with slight variation in the input parameters.

The significance of this thesis rests on the foundation that it provides a unique method of analysing the risks associated with CO₂ storage under geological formations from a qualitative point of view as well as a quantitative one. Furthermore, as well as the uniqueness of the subject analysis itself, it is also the first time that such methods have been used in order to carry out the said analyses. Moreover, the methods used within this research, namely the AHP, FTA and FAHP techniques have not been widely used in combination with each other to quantify the risks involved in industrial scale projects such as CCS. In addition, neither have they been previously used in combination with each other within the CCS industry nor have they been used on an individual basis. However, they have been used widely on their

own within other similar industries (similar in terms of the associated risk profiles) such as the nuclear, oil and gas and chemical industries.

Undertaking this research has resulted in the production of original mechanisms that can be used in order to calculate and estimate the criticality and importance of risks and therefore inspect the extent to which they have to be considered when storing CO₂ under geological formations. Additionally, original regulatory and legislative mechanisms have been developed that enable the Member States' Governments to place a cap on the long-term liability of CO₂ storage and otherwise to assist in the management of financial, liability and regulatory risks.

The analysis of the regulatory and legislative matters with regards to CO₂ storage together with the quantitative risk assessment methods used within this research have further developed and enriched the risk assessment methodology used within the Commission Guidance Documents. Therefore, the said analyses can serve as useful tools and mechanisms for insuring the risks associated with the storage of CO₂ in underground geological formations.

8.1 Challenges

In order to undertake this research, numerous methods were employed. As described in detail in chapter 5, in order to obtain stakeholder participation with regards to the risks associated with the storage of CO₂ under geological formations, a comprehensive expert survey was designed.

To the extent that was possible, it was made sure that the survey was distributed evenly amongst national and international experts within academia and the industry. Arguably, the response rates from the international stakeholder groups could have been higher. However, extensive efforts were made in order to increase the number of international experts to respond to the survey by telephone, email and approaching them at two major CCS-related conferences. Despite best efforts, no further responses were received. Furthermore, a total of 55 national and international experts responded to the surveys. Many more experts expressed the initial interest to partake in this study when approached in said conferences. However,

despite showing initial interest, many did not respond to the surveys when contacted afterwards.

However, some of the experts who responded to the surveys also provided extensive qualitative feedback in the comment box that was provided for each question within the survey which was beneficial to this research. As such, it influenced the research and was incorporated in the findings.

Experts were asked to complete the surveys taking into account only the first and second level in the overall risk hierarchy in order to simplify the risk analysis calculation process. In retrospect however, it would have been easier in survey terms to only focus upon risks on the first level of the fault tree, carry out the risk analysis procedure, interpret the results of the risk analysis calculations to trace the source of the risk and then apply the same procedure to the second, third and fourth levels in future research.

Furthermore, perhaps it would have been more efficient if some parts of the introductory email, project background and project methodology were deleted in order to reduce the amount of time experts had to spend on completing the questionnaires. This could have potentially increased the response rate. Moreover, different versions of the same questionnaire should have been designed for different categories of experts in order to better identify the experts that cooperated and took part in the study. This could have been potentially useful for future research as well as for this project.

8.2 Further Research

Several areas in this research have been identified that deserve further attention in future research. For example, there may be those that point to state aids and competition law restrictions on regulatory solutions for financial instruments for long term liability regulation further to the CCS Directive. It is noted that, to date, the UK and German Governments have taken a favourable position in this regard by adopting a flexible approach to state aids and it would appear that the European Commission is similarly disposed. There is also a strong argument to suggest that, in its essence, CO₂ storage represents a public good or service that fulfils a government function of mitigating climate change.

By storing CO₂ that would otherwise have been inevitably produced, in order to satisfy energy demand, storage serves to mitigate climate change and to meet binding emissions reduction targets that are placed upon Governments within an EU and international legal context. Given the additional point that CO₂ storage may well turn out to be a cost vs. revenue neutral activity, some easing of state aids rules/competition law should apply. This argumentation is supported by the EC Treaty obligation of competition law to not obstruct the performance, in law or in fact, of the particular tasks assigned to services of general economic interest (i.e., arguably, the provision of CO₂ storage for climate change prevention and mitigation).

Thus far, leading Member State Governments have taken a sensible approach to state aid regulation and CCS. For this reason, it is not suggested that a formal procedure be commenced to review the EU General Block Exemption Regulation or Guidelines for State Aid for Environmental Protection with the aim of codifying new principles and rules in respect of CCS. This would constitute a drawn out and cumbersome process. Given the history of CCS Directive negotiation, there would be further uncertainty about the result and Member States and non-State interests, which are without direct and active interests and projects in the field of CCS, would still be in a position to influence the outcome in a manner that may not best serve Member States and private sector actors that wish to advance the CCS technology. There is also the observation that the revision of EU state aids regulation and guidance for CCS should have taken place at a time that was commensurate with the creation of the CCS Directive. Re-opening the debate would only lead to further market uncertainty at a time when the CCS Directive is due shortly to enter into force¹⁰. In any event, the signs are that a flexible approach is being taken by CCS implementing states to the interpretation of state aids disciplines. As such, it is anticipated that regulators will continue along these lines and that this approach will be reinforced in the final draft of the GD4 document. The issues raised require more detailed treatment but are beyond the scope of this research.

As mentioned before, sensitivity analysis was carried out using Fuzzy logic in order to account for possible subjectivity and ambiguity associated with experts' opinion in order to assess whether or not the results obtained as a result of the risk modelling would differ should

¹⁰ At the time of writing this section of the thesis, June 2011.

there be little variation in the input parameters. The Fuzzy logic was applied to the AHP method and as a result, the FAHP method was conducted.

In order to inspect the possibility of a change in the final result of the modelling techniques used in this research, it would be beneficial to apply the Fuzzy logic to the other methods used in this research, i.e. Fuzzy TOPSIS and Fuzzy PROMETHEE.

Additionally, it would also be useful to inspect whether using other systems engineering optimisation techniques such as ELECTRE (Elimination Et Choice Translating Reality), ENTROPY and SAW (Simple Additive Weighted) would result in the same order for the ranking of the risks associated with CO₂ storage.

Finally, the regulatory and related EU Guidance Document analysis herein should be considered in the context of stakeholder and scholarly submissions to the recently announced CCS Directive review process. In this regard, it is felt that the analysis in this thesis for addressing risk could lead to the improvement of the Directive and the EU Guidance Documents.

CHAPTER 9

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9 REFERENCES

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CHAPTER 10

APPENDICES

10 APPENDICES

10.1 Appendix I

10.1.1 TOPSIS Methodology and its Application

In order to be able to use the TOPSIS method, decision makers have to have knowledge of the relative weights of the criteria. Macharis et al. proposed that for large amounts of data, the relative weights can be calculated using methods such as: direct rating, point allocation, trade-off, pair-wise comparisons, and so on (Macharis et al., 2004). For this purpose, the pair-wise comparison method i.e. the AHP method has been chosen in order to provide the input parameters i.e. the relative weights of the criteria for the TOPSIS method. This was owing to the fact that as described in chapter 4, as part of the AHP method, an expert survey was sent to experts within the field of geological storage of carbon dioxide underground. Furthermore, the results from the survey provided the input parameters for the AHP method which in turn can also be used for the TOPSIS method.

The way in which the TOPSIS technique is performed is as follows:

1. In this algorithm, the inputs are in the form a Weighted Normalised Matrix, v_{ij} , which can be seen in equation 21. This matrix is obtained as a result of the multiplication of equations 8 and 9.

$$v_{ij} = R_{ij} \times w_i = \begin{bmatrix} r_{11}w_1 & \cdots & r_{1J}w_n \\ \vdots & \ddots & \vdots \\ r_{n1}w_1 & \cdots & r_{nJ}w_n \end{bmatrix}; \quad i = 1, \dots, n; j = 1, \dots, J$$

Equation 21, TOPSIS: Weighted Normalised Matrix

2. Using the weighted normalised matrix, the Positive-Ideal, A^* , and Negative-Ideal, A^- , solutions are determined using equations 22 and 23 respectively.

$$A^* = \{v_1^*, v_2^*, \dots, v_n^*\} = \left\{ \left(\max_{ij} v_{ij} \mid j \in I' \right), \left(\min_i v_{ij} \mid j \in I'' \right) \right\}$$

Equation 22, TOPSIS: Positive-Ideal Solution

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \left\{ \left(\min_{ij} v_{ij} \mid j \in I' \right), \left(\max_i v_{ij} \mid j \in I'' \right) \right\}$$

Equation 23, TOPSIS: Negative-Ideal Solution

Where, I' is associated with the benefit criteria and I'' is associated with the cost criteria.

3. The alternative's distance from the positive-ideal d_j^+ and negative-ideal d_j^- solutions, known as the Euclidean distance, are calculated using equations 24 and 25 respectively.

$$d_j^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}; i = 1, 2, \dots, m$$

Equation 24, TOPSIS: Alternative's distance from positive-ideal solution

$$d_j^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}; i = 1, 2, \dots, m$$

Equation 25, TOPSIS: Alternative's distance from negative-ideal solution

4. Now the Relative Closeness (CL_j^*) of each alternative to the ideal solution has to be determined. CL_j^* is calculated using equation 26.

$$CL_j^* = \frac{d_j^-}{d_j^- + d_j^+}$$

Equation 26, TOPSIS: Relative Closeness of each alternative to the ideal solution

Since $d_j^- \geq 0$ and $d_j^+ \geq 0$, then clearly $CL_j^+ \in [0,1]$.

5. Finally, as result of these analyses, it will be concluded that the alternative that has the maximum CL_j^+ , is the appropriate alternative. All the other alternatives' distances to the negative and positive ideal solutions are calculated in the same way.

What follows is the way in which the TOPSIS method described above was used in order to calculate ranking for the main risks involved in CO₂ storage.

In order to be able to use the TOPSIS method, one has to know the relative weights of the criteria and alternatives. Furthermore, using the AHP method, the said weights were calculated and are shown in tables 40 and 41.

	Alternatives' Weights											
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2
A	0.726	0.570	0.467	0.138	0.711	0.046	0.068	0.058	0.062	0.114	0.059	0.078
B	0.094	0.064	0.407	0.566	0.195	0.116	0.074	0.110	0.065	0.076	0.061	0.081
C	0.088	0.184	0.048	0.159	0.048	0.385	0.555	0.458	0.345	0.475	0.313	0.137
D	0.091	0.182	0.079	0.137	0.047	0.454	0.303	0.375	0.529	0.335	0.567	0.704

Table 40, TOPSIS: Weight of different alternatives calculated using the AHP method

Criteria Weights	
a1	0.032
a2	0.029
b1	0.018
b2	0.025
b3	0.042
c1	0.153
c2	0.162
c3	0.156
c4	0.133
c5	0.113
d1	0.068
d2	0.069

Table 41, TOPSIS: Criteria Weights calculated using the AHP method

Using equation 21, the Weighted Normalised Matrix, v_{ij} , is devised as below. As mentioned in the same section, this matrix has been developed as a result of multiplying equations 8 and 9. These matrices have been shown in tables 42 and 43.

Weighted Normalised Matrix (Multiplication Matrix)				
	A	B	C	D
a1	0.0232	0.0030	0.0028	0.0029
a2	0.0165	0.0019	0.0053	0.0053
b1	0.0084	0.0073	0.0009	0.0014
b2	0.0035	0.0142	0.0040	0.0034
b3	0.0299	0.0082	0.0020	0.0020
c1	0.0070	0.0177	0.0589	0.0695
c2	0.0110	0.0120	0.0899	0.0491
c3	0.0090	0.0172	0.0714	0.0585
c4	0.0082	0.0086	0.0459	0.0704
c5	0.0129	0.0086	0.0537	0.0379
d1	0.0040	0.0041	0.0213	0.0386
d2	0.0054	0.0056	0.0095	0.0486

Table 42, TOPSIS: The normalised weighted matrix

As shown in table 43, positive ideal solution (A^*) and negative ideal solution (A^-) is calculated for each alternative using equations 24 and 25 respectively.

Positive and Negative Ideal Solutions		
	A^*	A^-
a1	0.0232	0.0028
a2	0.0165	0.0019
b1	0.0084	0.0009
b2	0.0142	0.0034
b3	0.0299	0.0020
c1	0.0695	0.0070
c2	0.0899	0.0110
c3	0.0714	0.0090
c4	0.0704	0.0082
c5	0.0537	0.0086
d1	0.0386	0.0040
d2	0.0486	0.0054

Table 43, TOPSIS: Positive and Negative Ideal Solutions

Equations 24, 25 and 26 were used in order to calculate the alternatives' distance from the positive ideal solution (d_j^+), alternatives' distance from the negative ideal solution (d_j^-) and the relative closeness of each alternative to the ideal solution (CL_j^*) respectively.

Positive and Negative Distances and Relative Closeness				
	A	B	C	D
d_j^+	0.1507	0.1472	0.0634	0.0597
d_j^-	0.0385	0.0194	0.1288	0.1248
CL_i^*	0.2037	0.1166	0.6702	0.6764

Table 44, TOPSIS: Positive and negative distance and relative closeness of alternatives to ideal solution

Table 45 shows the ranking order for the criteria of this study using the TOPSIS method.

Risk ranking of the alternatives	
A	0.2037
B	0.1166
C	0.6702
D	0.6764

Table 45, Weight of the risks using TOPSIS

Table 46 shows the different risks analysed in this project and their rank in comparison to each other using the TOPSIS method. Moreover, this ranking is in terms of their criticality and their potential to cause the stored carbon dioxide in underground storage reservoirs to leak to the atmosphere and cause harm to humans and the environment.

Risk ranking of the alternatives	Rank
Percolation of CO ₂ through the caprock (A)	3
Migration of CO ₂ along a fracture or permeable zone (B)	4
Leakage of CO ₂ through or along the injection well (C)	2
Leakage of CO ₂ through other wells (D)	1

Table 46, Ranking of the risks using TOPSIS

10.1.2 PROMETHEE Methodology and its Application

The way in which the PROMETHEE method is carried out is as follows:

1. The amplitude of deviation d_i between the evaluation of each alternative k and l , within each element i , is calculated using equation 27.

$$d_i(k, l) = r_{ki} - r_{li}, k, l = 1, 2, \dots, J \text{ and } i = 1, 2, \dots, n$$

Equation 27, PROMETHEE: Amplitude of deviation d_i between the evaluation of each alternative k and l within each attribute i

Therefore, deviation amplitude matrix for an alternative j within n attributes can be calculated using equation 28.

$$D_j = \begin{bmatrix} d_1(j, 1) & d_2(j, 1) & \dots & d_n(j, 1) \\ d_1(j, 2) & d_2(j, 2) & \dots & d_n(j, 2) \\ \vdots & \vdots & \ddots & \vdots \\ d_1(j, J) & d_2(j, J) & \dots & d_n(j, J) \end{bmatrix}, j = 1, 2, \dots, J$$

Equation 28, PROMETHEE: Deviation amplitude matrix for an alternative j within n attributes

2. Equation 29 shows the Gaussian function used as a preference function, $P_i(d)$ for each criterion i .

$$P_i(d) = \begin{cases} 0, & \text{if } d_i \leq 0 \\ 1 - \exp\left(\frac{-d_i^2}{2\sigma^2}\right) & \text{if } d_i > 0 \end{cases}$$

Equation 29, PROMETHEE: Gaussian function used as a preference function

The preference function $P_i(k,l)$ for each criterion i and alternatives k and l , is shown in equation 30.

$$P_i(k,l) = \begin{cases} \text{if } r_{ki} \leq r_{li} \Rightarrow d_i(k,l) \leq 0 \rightarrow P_i(k,l) = 0 \\ \text{if } r_{ki} > r_{li} \Rightarrow d_i(k,l) < 0 \rightarrow P_i(k,l) = 1 - \exp\left(\frac{-d_i^2}{2\sigma^2}\right) \end{cases}$$

Equation 30, PROMETHEE: preference function $P_i(k,l)$ for each criterion i and alternatives k and l

If alternative k , based on criterion i , is similar or worse than alternative l , then the preference function will be zero. However, if alternative k , based on criterion i , is better than alternative l , the preference function will be between 0 and 1. Furthermore, wherever the preference function is close to 1, the distance between the normalized values of r_{ki} and r_{li} increase.

Based on the Gaussian preference function for determination of the inflexion point of the curve, equation 31 is used in order to calculate the threshold value of parameter σ .

$$\sigma_i = \frac{\sum_{\substack{k,l=1 \\ k \neq l}}^{k,l=J} |d_i(k,l)|}{J(J-1)}; \quad i = 1, 2, \dots, n; k, l = 1, 2, \dots, J$$

Equation 31, PROMETHEE: threshold value of parameter σ

3. Now the preference index has to be calculated. The preference index $\Pi(k,l)$ is calculated using equation 32 which indicates the preference value of alternative A_k over alternative A_l .

$$\Pi(k,l) = \sum_{i=1}^n w_i \cdot P_i(k,l); \quad k,l \in J$$

Equation 32, PROMETHEE: Calculation of the preference index

4. After calculating the preference index, $\Pi(k,l)$, the preference index matrix is calculated using equation 33.

$$\Pi = \begin{bmatrix} 0 & \Pi(1,2) & \dots & \Pi(1,J) \\ \Pi(2,1) & 0 & \dots & \Pi(2,J) \\ \vdots & \vdots & \ddots & \vdots \\ \Pi(J,1) & \Pi(J,2) & \dots & 0 \end{bmatrix}; \quad i,j = 1,2,\dots,J$$

Equation 33, PROMETHEE: Calculation of the preference index matrix

5. The outgoing flow (Φ_j^+) is calculated using equation 34. The outgoing flow is the sum of the value of arcs which leave node j and therefore yields a measure of the *outranking character* of alternative j . The outgoing flow indicates the strength of alternative j .

$$\Phi_j^+ = \frac{1}{J-1} \sum_{\substack{k=1 \\ k \neq j}}^J \Pi(j,k); \quad j,k = 1,2,\dots,J$$

Equation 34, PROMETHEE: The outgoing flow

6. The entering flow (Φ_j^-) is calculated using equation 35. The entering flow is a measure of the weakness of an alternative j .

$$\Phi_j^- = \frac{1}{J-1} \sum_{\substack{k=1 \\ k \neq j}}^J \Pi(k, j); \quad j, k = 1, 2, \dots, J$$

Equation 35, PROMETHEE: The entering flow

7. The alternatives are ranked using the *net flow* (Φ_j^{net}) which is calculated using equation 36.

$$\Phi_j^{net} = \Phi_j^+ - \Phi_j^-$$

Equation 36, PROMETHEE: The net flow

As mentioned in section 7.4.2, in order for decision makers to be able to use the PROMETHEE method, two requirements have to be met. Firstly, relative importance of the criteria that is being considered has to be taken into account. This has also been referred to as the “relative weight of the criteria within the theses.

Secondly, decision makers’ preference function, which he/she uses when comparing the contribution of the alternatives in terms of each separate criterion (Macharis et al., 2004).

As highlighted in the thesis, since the PROMETHEE technique does not provide guidelines as regards to the relative weights of the criteria being considered, different people have developed different methods that enables decision makers to determine relative weights of the criteria in order to use within the algorithm (see (Nijkamp et al., 1990), (Eckenrode, 1965) and (Macharis et al., 2004) for an overview of these methods). For the purpose of this research project, the AHP method has been chosen in order to provide the input parameters i.e. the relative weights of the criteria for the PROMETHEE method.

Therefore, the relative weights that were calculated using the AHP method (shown in table 47) have been used in order to construct the matrix of deviation amplitude for normalised values which is shown in table 48.

	Alternatives' Weights											
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2
A	0.726	0.570	0.467	0.138	0.711	0.046	0.068	0.058	0.062	0.114	0.059	0.078
B	0.094	0.064	0.407	0.566	0.195	0.116	0.074	0.110	0.065	0.076	0.061	0.081
C	0.088	0.184	0.048	0.159	0.048	0.385	0.555	0.458	0.345	0.475	0.313	0.137
D	0.091	0.182	0.079	0.137	0.047	0.454	0.303	0.375	0.529	0.335	0.567	0.704

Table 47, PROMETHEE: Weight of different alternatives calculated using AHP

Matrix of deviation amplitude for normalised values													
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2	
A-B	0.632	0.506	0.060	-0.428	0.516	-0.070	-0.006	-0.052	-0.003	0.038	-0.002	-0.003	
A-C	0.638	0.386	0.419	-0.021	0.663	-0.339	-0.487	-0.400	-0.283	-0.361	-0.254	-0.059	
A-D	0.635	0.388	0.388	0.001	0.664	-0.408	-0.235	-0.317	-0.467	-0.221	-0.508	-0.626	
B-A	-0.632	-0.506	-0.060	0.428	-0.516	0.070	0.006	0.052	0.003	-0.038	0.002	0.003	
B-C	0.006	-0.120	0.359	0.407	0.147	-0.269	-0.481	-0.348	-0.280	-0.399	-0.252	-0.056	
B-D	0.003	-0.118	0.328	0.429	0.148	-0.338	-0.229	-0.265	-0.464	-0.259	-0.506	-0.623	
C-A	-0.638	-0.386	-0.419	0.021	-0.663	0.339	0.487	0.400	0.283	0.361	0.254	0.059	
C-B	-0.006	0.120	-0.359	-0.407	-0.147	0.269	0.481	0.348	0.280	0.399	0.252	0.056	
C-D	-0.003	0.002	-0.031	0.022	0.001	-0.069	0.252	0.083	-0.184	0.140	-0.254	-0.567	
D-A	-0.635	-0.388	-0.388	-0.001	-0.664	0.408	0.235	0.317	0.467	0.221	0.508	0.626	
D-B	-0.003	0.118	-0.328	-0.429	-0.148	0.338	0.229	0.265	0.464	0.259	0.506	0.623	
D-C	0.003	-0.002	0.031	-0.022	-0.001	0.069	-0.252	-0.083	0.184	-0.140	0.254	0.567	

Table 48, PROMETHEE: Matrix of deviation amplitude for normalised values

The value of threshold for each alternative, σ , is calculated based on the Gaussian preference function for determination of the inflexion point of the curve using equation 31 and shown in table 49 below.

Values of threshold (σ)												
Criteria	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2
Threshold	0.319	0.253	0.264	0.218	0.356	0.248	0.281	0.244	0.28	0.236	0.296	0.322

Table 49, PROMETHEE: The values of threshold for each alternative (σ)

Having calculated the vales of threshold and the matrix deviation amplitude, the preference function is calculated using equation 32 and shown in table 50.

Preference function													
	a1	a2	b1	b2	b3	c1	c2	c3	c4	c5	d1	d2	
P(A,B)	0.858	0.863	0.025	0.000	0.649	0.000	0.000	0.000	0.000	0.012	0.000	0.000	
P(A,C)	0.861	0.690	0.715	0.000	0.822	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
P(A,D)	0.000	0.000	0.000	0.000001	0.823	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
P(B,A)	0.0001	0.000	0.602	0.854	0.000	0.038	0.0002	0.022	0.00005	0.000	0.00002	0.00004	
P(B,C)	0.00004	0.000	0.537	0.824	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
P(B,D)	0.000	0.000	0.000	0.855	0.082	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
P(C,A)	0.000	0.000	0.000	0.004	0.000	0.604	0.775	0.738	0.399	0.688	0.308	0.016	
P(C,B)	0.000	0.106	0.000	0.000	0.000	0.442	0.767	0.637	0.393	0.759	0.303	0.014	
P(C,D)	0.000	0.0000	0.000	0.005	0.000004	0.000	0.329	0.056	0.000	0.160	0.000	0.000	
P(D,A)	0.000	0.000	0.000	0.000	0.000	0.739	0.293	0.569	0.750	0.354	0.770	0.848	
P(D,B)	0.000	0.102	0.000	0.000	0.000	0.602	0.281	0.445	0.746	0.451	0.768	0.845	
P(D,C)	0.00004	0.000	0.006	0.000	0.000	0.037	0.000	0.000	0.193	0.000	0.308	0.787	

Table 50, PROMETHEE: Preference function matrix

Table 51 shows the matrix of preference index which has been derived using equation 32 and equation 33.

Matrix of preference index				
	A	B	C	D
A	0.0000	0.0817	0.0950	0.0941
B	0.0308	0.0000	0.0349	0.0345
C	0.4866	0.4544	0.0000	0.0805
D	0.5004	0.4710	0.1070	0.0000

Table 51: PROMETHEE: Matrix of preference index

Moreover, table 52 shows the outgoing flow, Φ_j^+ , and the entering flow, Φ_j^- , which are calculated using equation 34 and equation 35 respectively. Furthermore, table 52 also shows the net flow, Φ_j^{net} , which is calculated using equation 36.

All flows and ranking of alternatives				
	A	B	C	D
Outgoing flow (+)	0.0902	0.0334	0.3405	0.3595
Entering flow (-)	0.3393	0.3357	0.0789	0.0697
Net flow	-0.2490	-0.3023	0.2615	0.2898
Ranking	3	4	2	1

Table 52, PROMETHEE, Outgoing Flow, Entering Flow and Net Flow

Table 53 shows the ranking of the criteria of this study using the PROMETHEE method.

Risk ranking of the alternatives	
A	-0.2490
B	-0.3023
C	0.2615
D	0.2898

Table 53, Weight of the risks using PROMETHEE

Table 54 shows the ranking of the different risks that were analysed in this research using the PROMETHEE method.

Risk ranking of the alternatives	Rank
Percolation of CO ₂ through the caprock (A)	3
Migration of CO ₂ along a fracture or permeable zone (B)	4
Leakage of CO ₂ through or along the injection well (C)	2
Leakage of CO ₂ through other wells (D)	1

Table 54, Ranking of the risks using PROMETHEE

10.1.3 Calculation steps of the AHP method

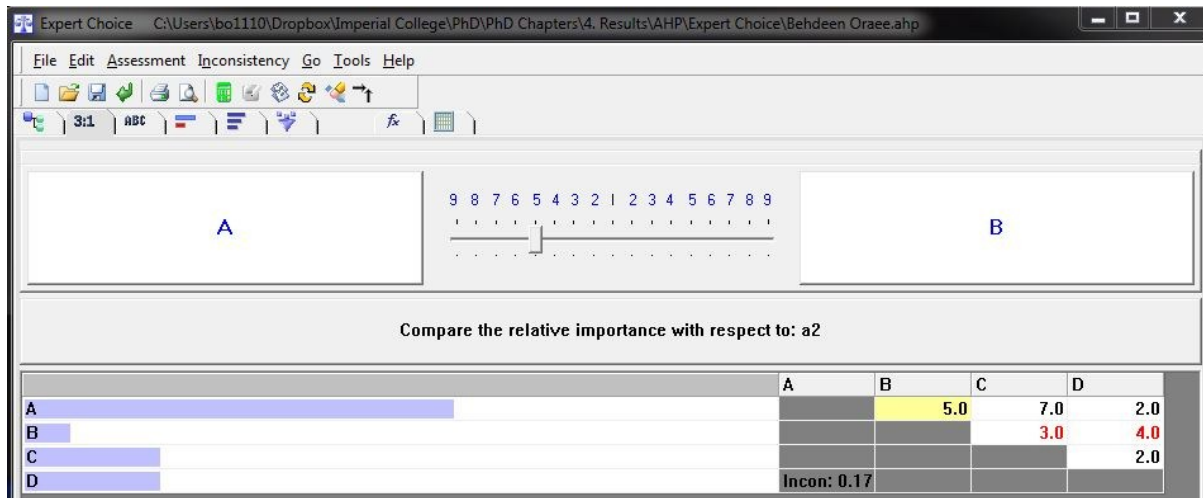


Figure 25, Comparison of alternatives with respect to “a₂” using a numerical scale

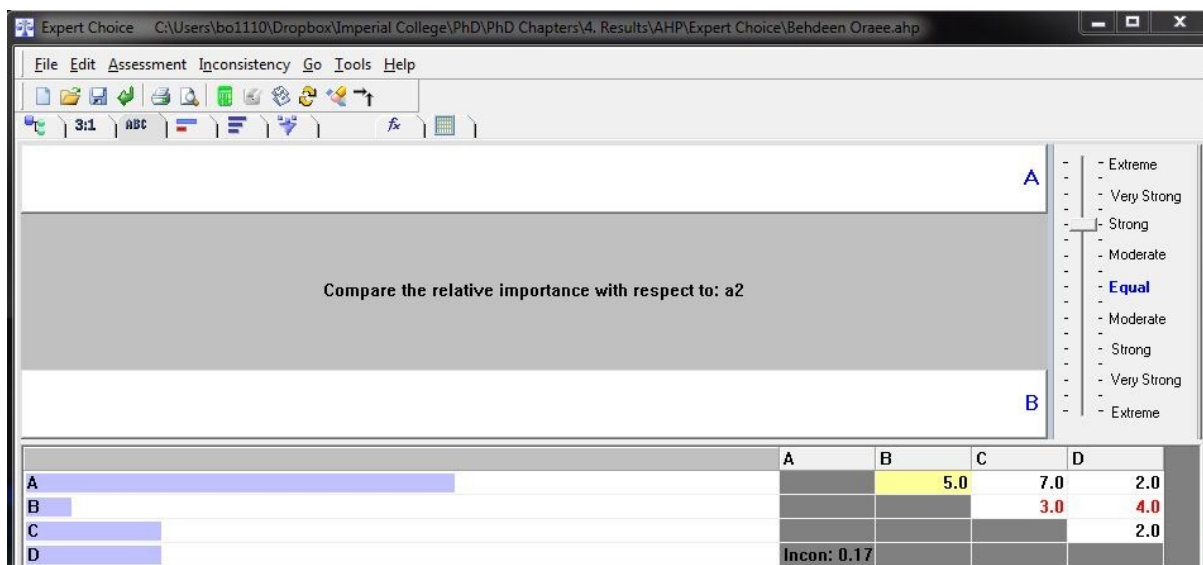


Figure 26, Comparison of alternatives with respect to “a₂” using a linguistic scale

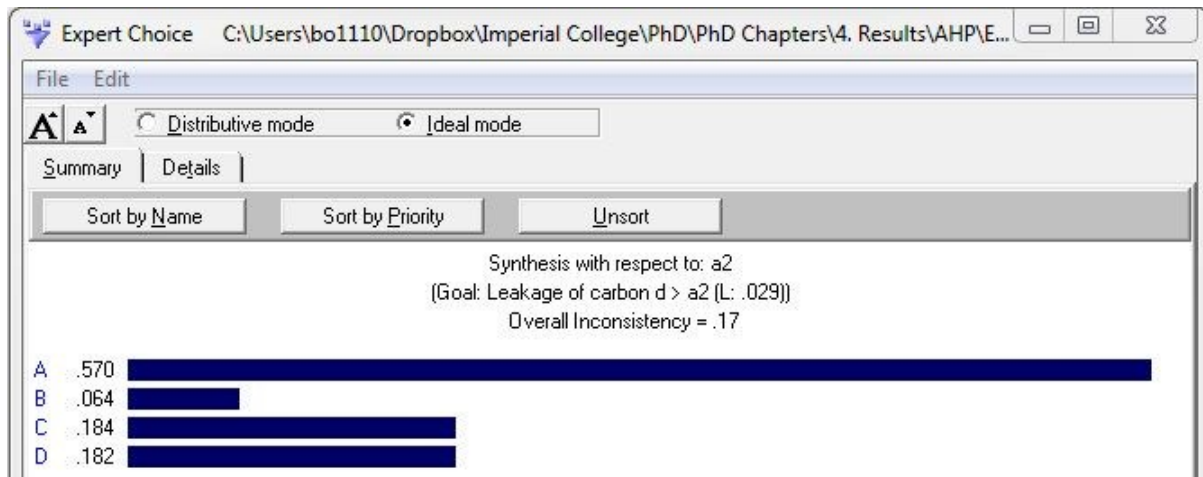


Figure 27, Final weight of alternatives with respect to “a₂”

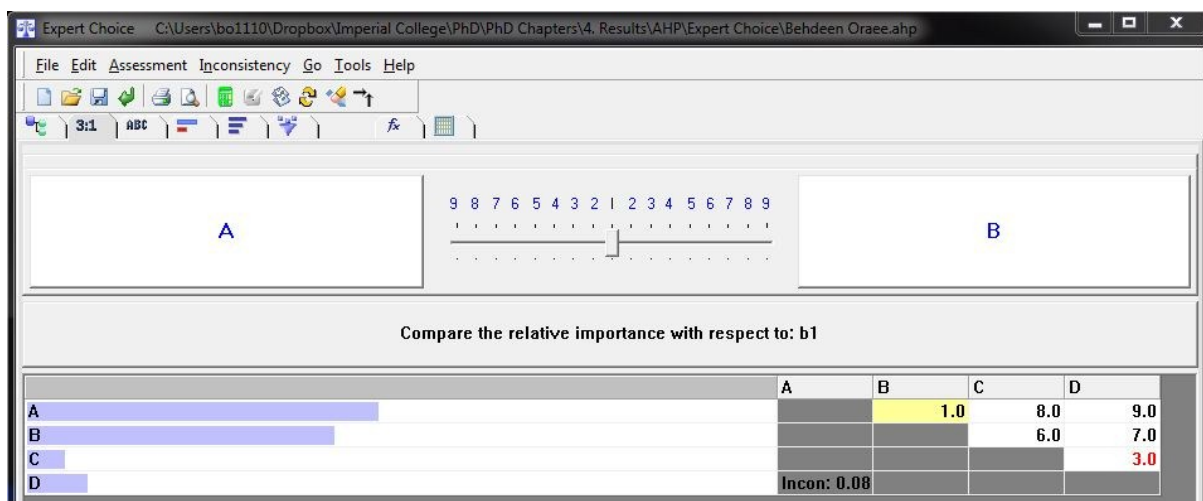


Figure 28, Comparison of alternatives with respect to “b₁” using a numerical scale

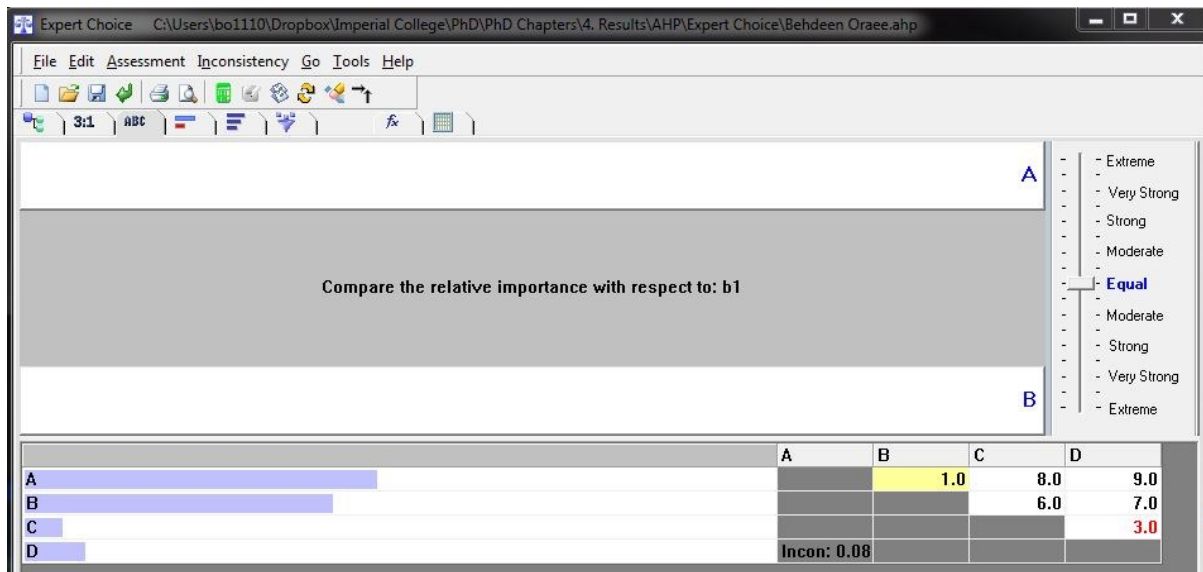


Figure 29, Comparison of alternatives with respect to “ b_1 ” using a linguistic scale

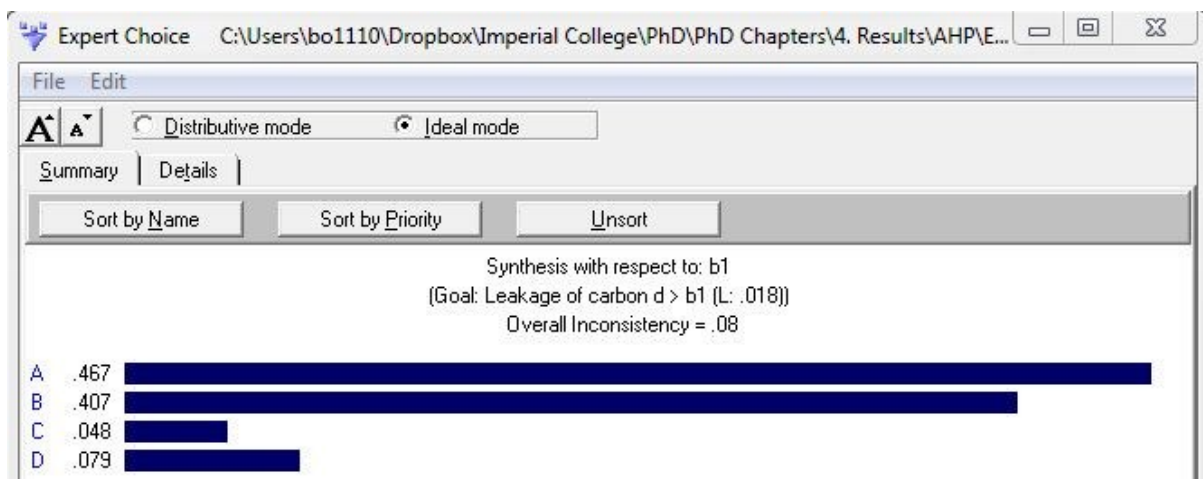


Figure 30, Final weight of alternatives with respect to “ b_1 ”

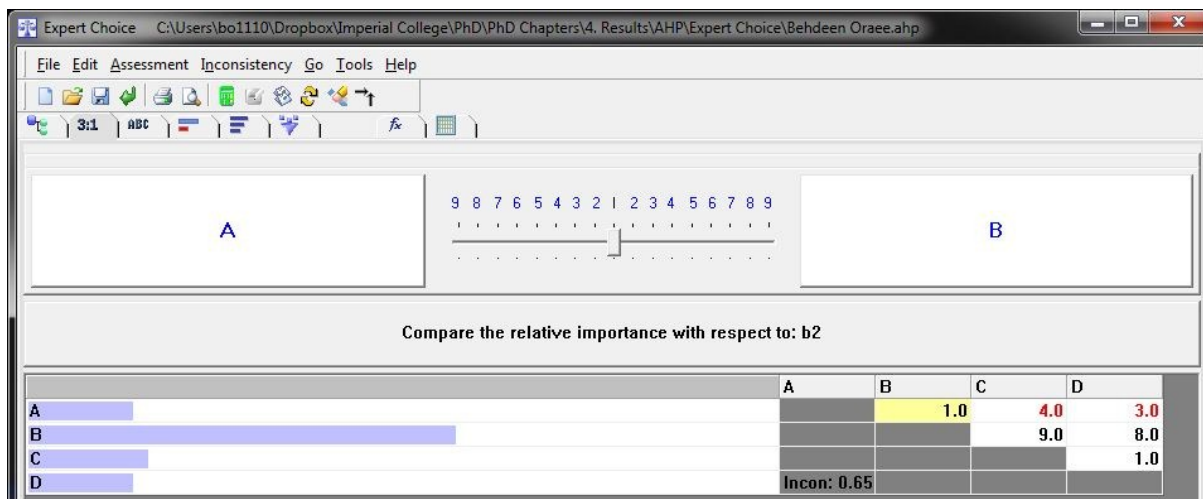


Figure 31, Comparison of alternatives with respect to “ b_2 ” using a numerical scale

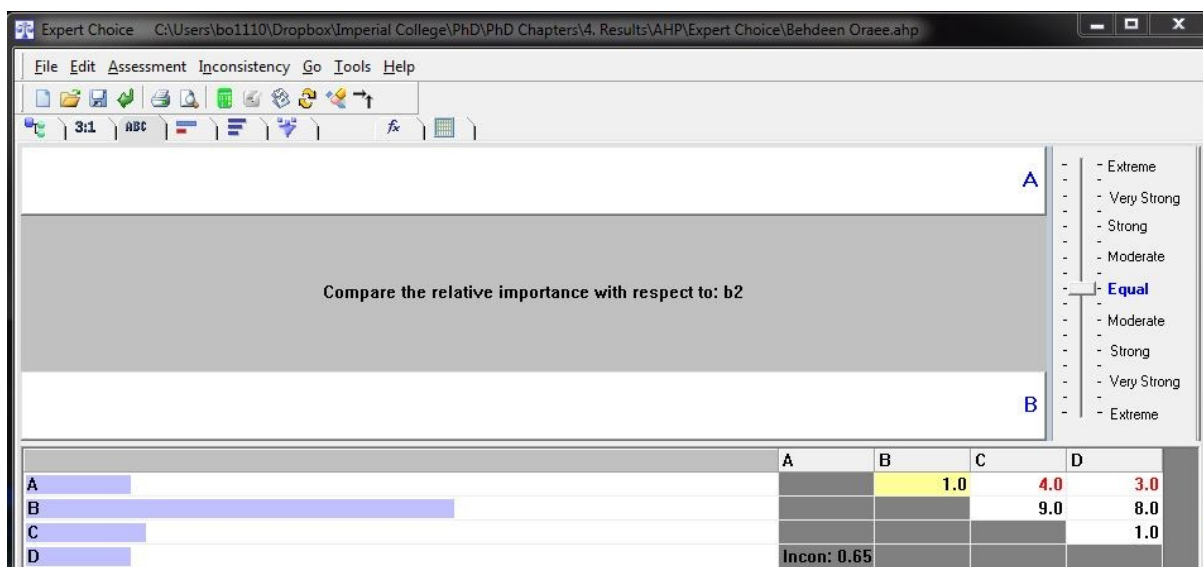


Figure 32, Comparison of alternatives with respect to “ b_2 ” using a linguistic scale

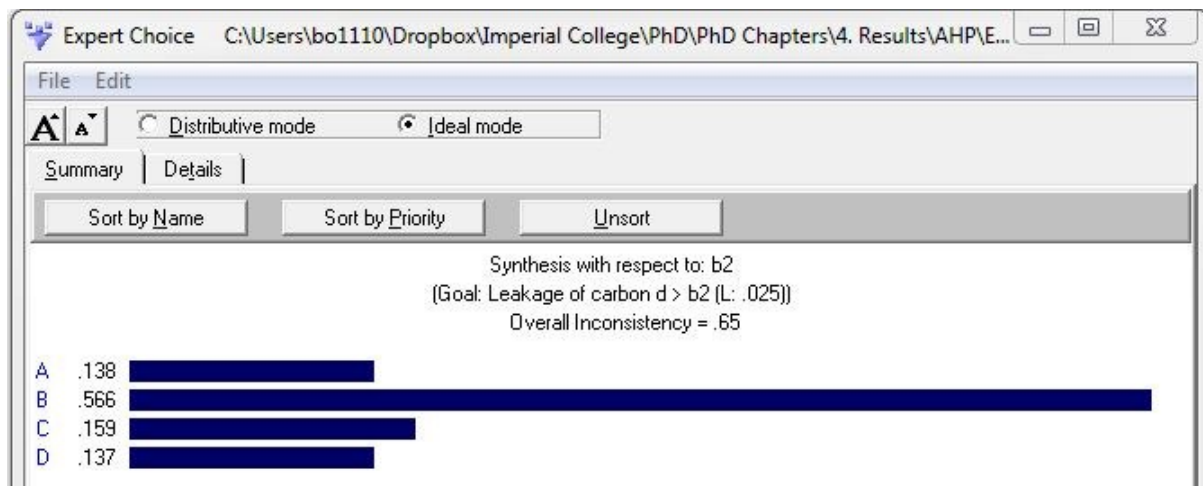


Figure 33, Final weight of alternatives with respect to “ b_2 ”

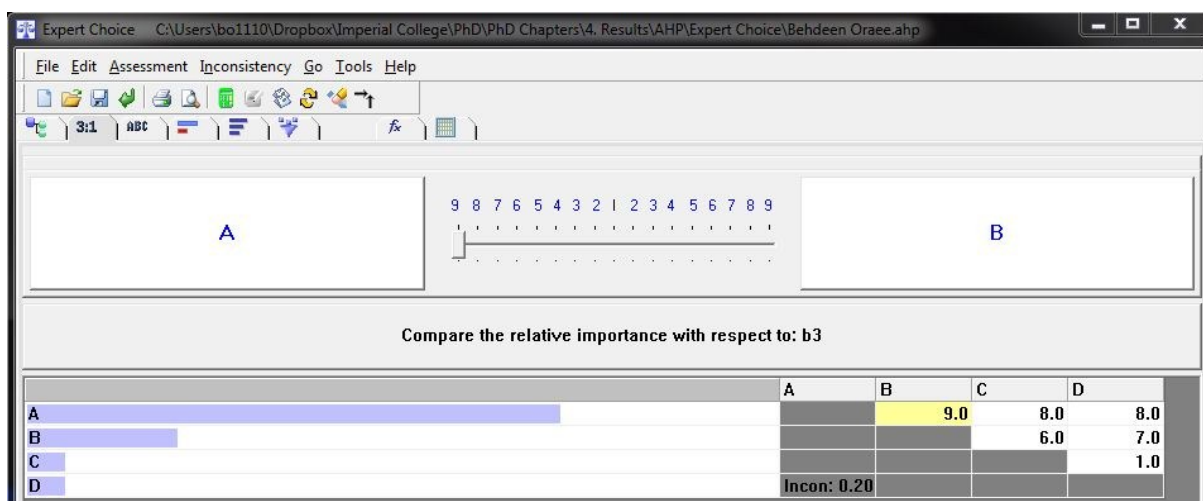


Figure 34, Comparison of alternatives with respect to “ b_3 ” using a numerical scale

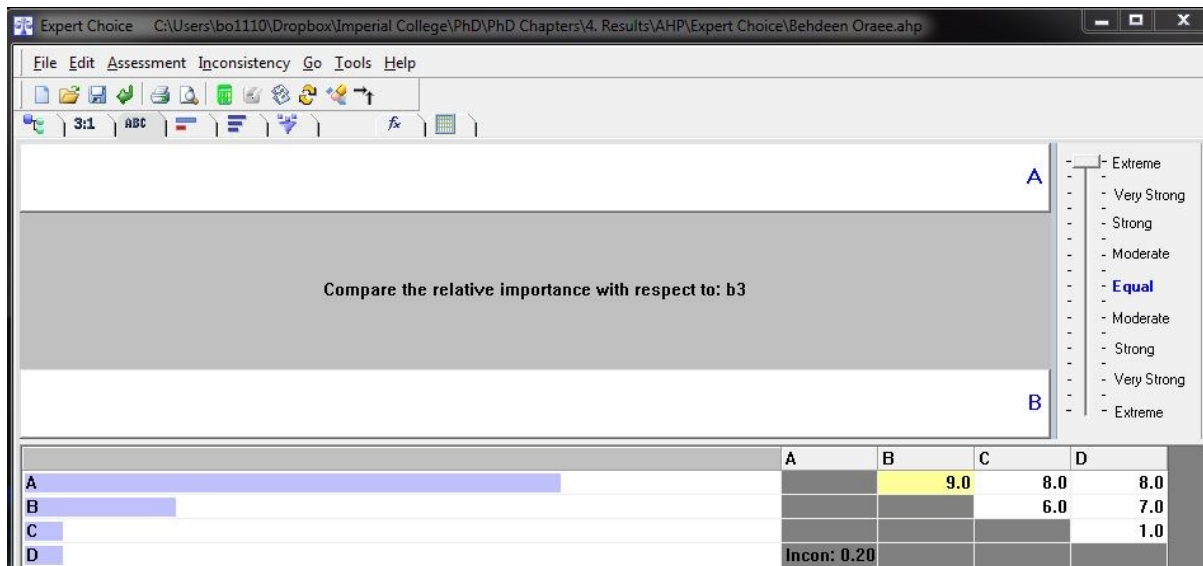


Figure 35, Comparison of alternatives with respect to “b₃” using a linguistic scale

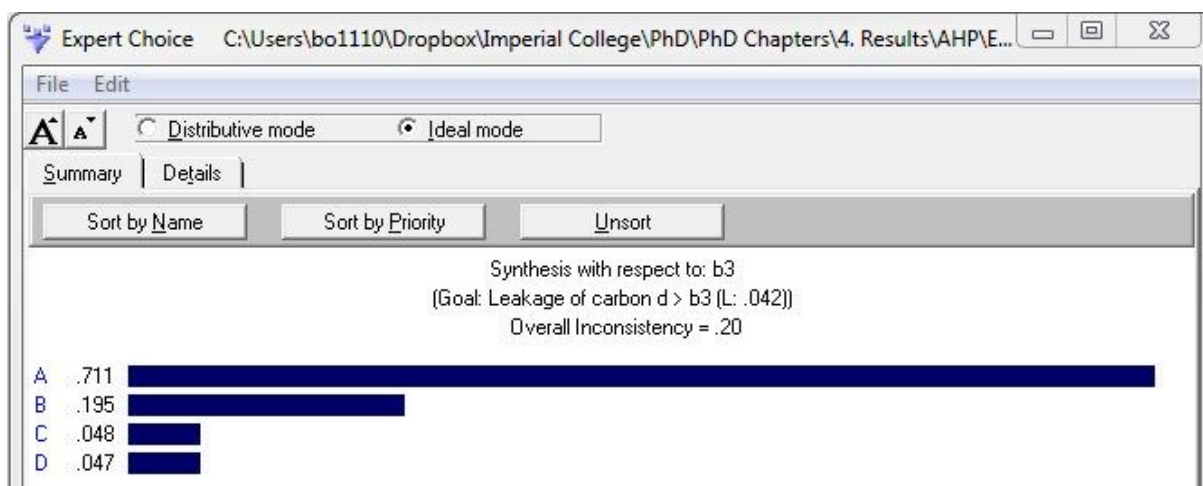


Figure 36, Final weight of alternatives with respect to “b₃”

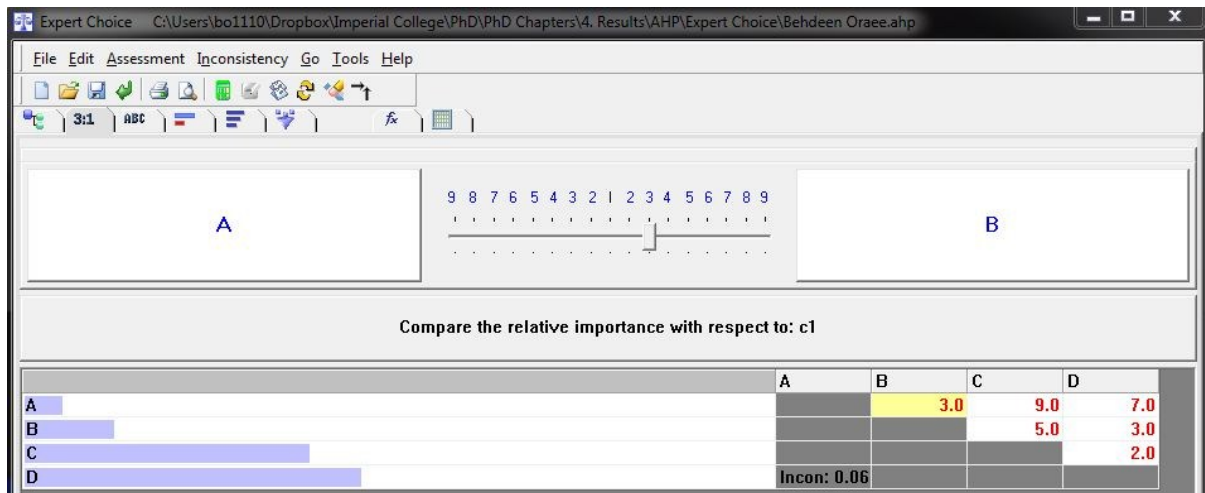


Figure 37, Comparison of alternatives with respect to “ c_1 ” using a numerical scale

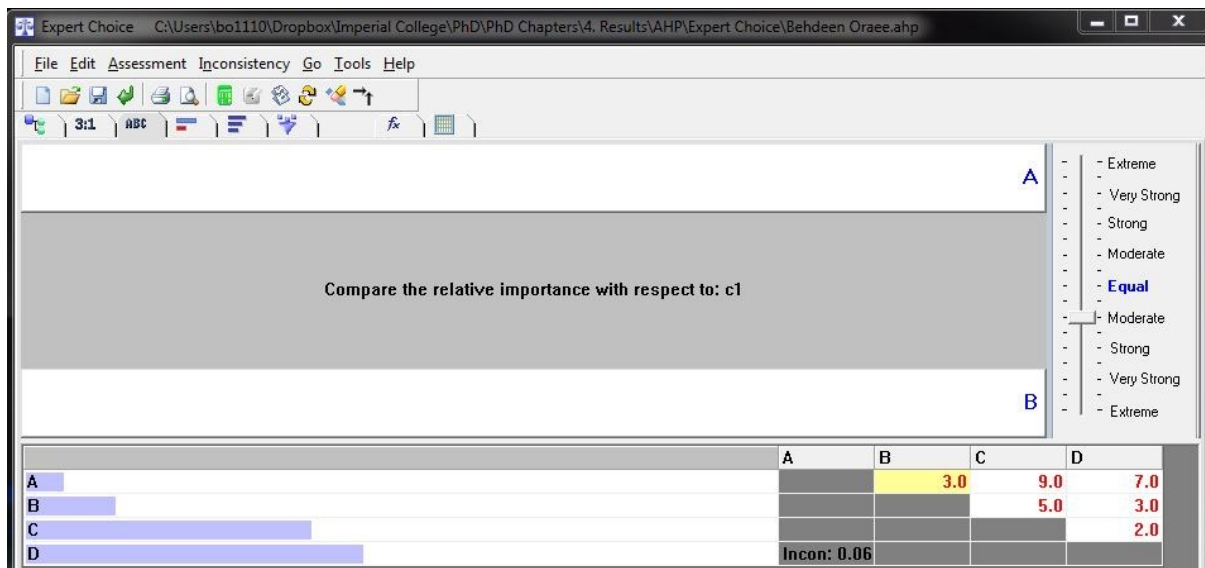


Figure 38, Comparison of alternatives with respect to “ c_1 ” using a linguistic scale

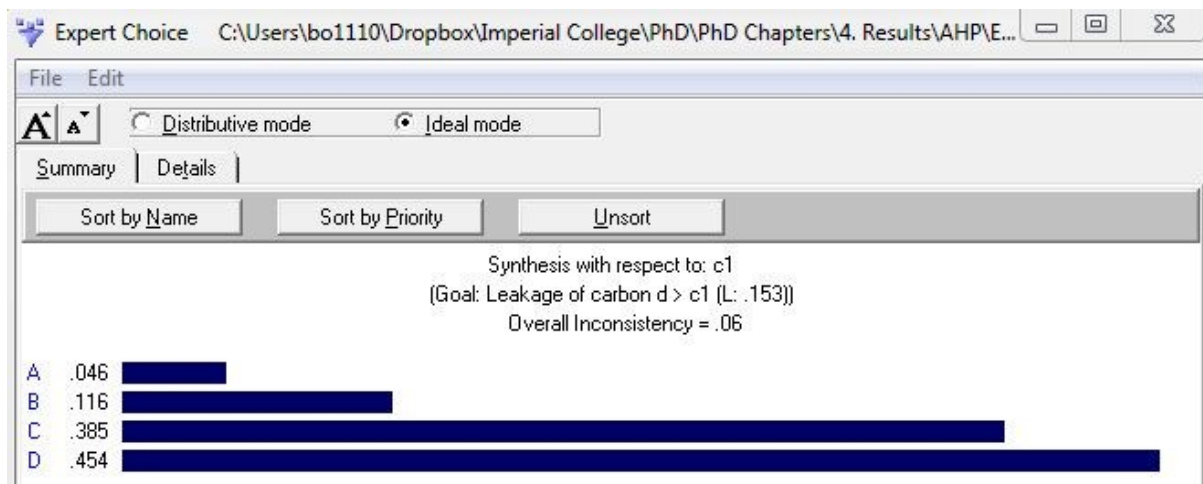


Figure 39, Final weight of alternatives with respect to “ c_1 ”

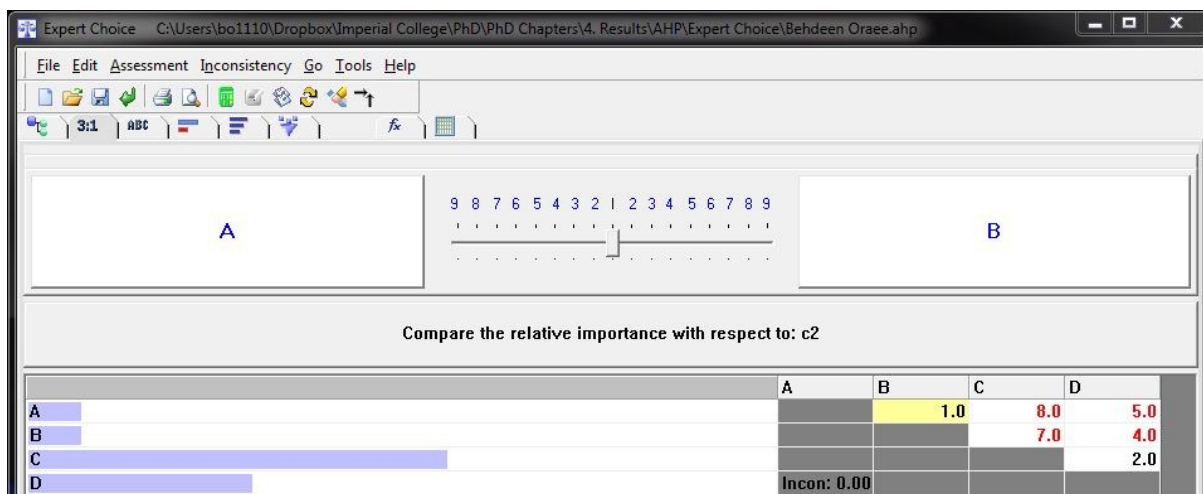


Figure 40, Comparison of alternatives with respect to “ c_2 ” using a numerical scale

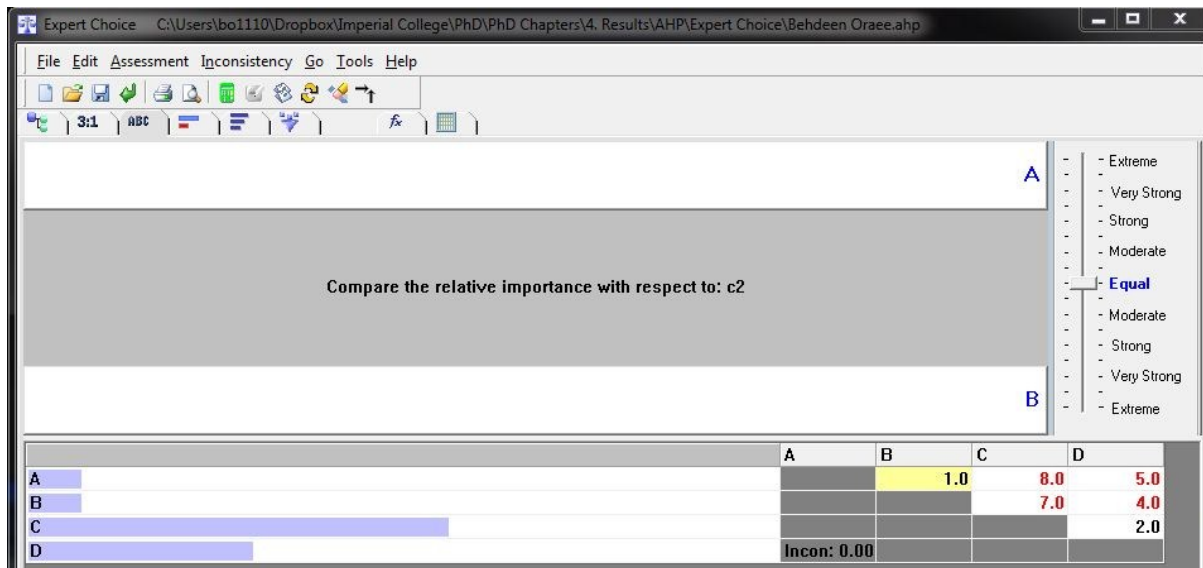


Figure 41, Comparison of alternatives with respect to “ c_2 ” using a linguistic scale

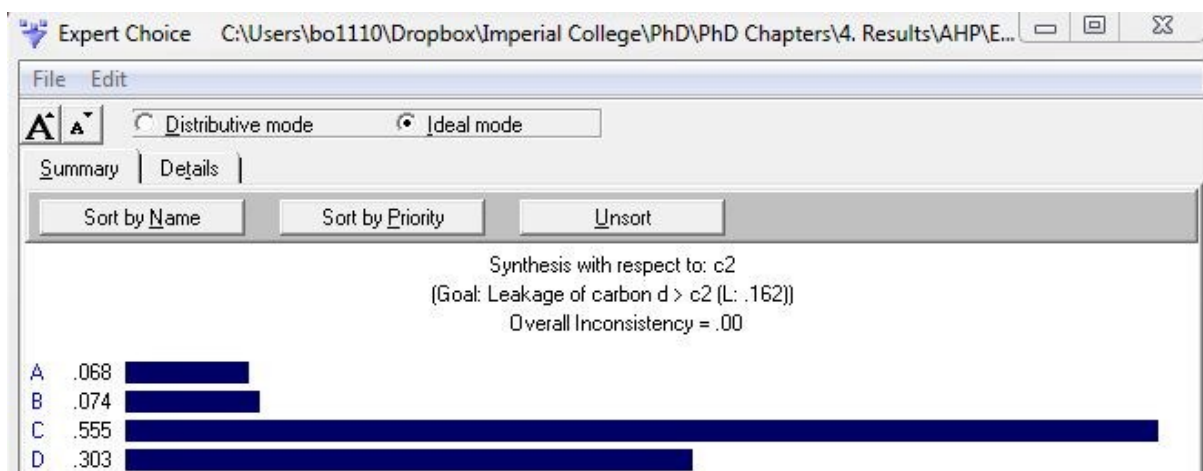


Figure 42, Final weight of alternatives with respect to “ c_2 ”

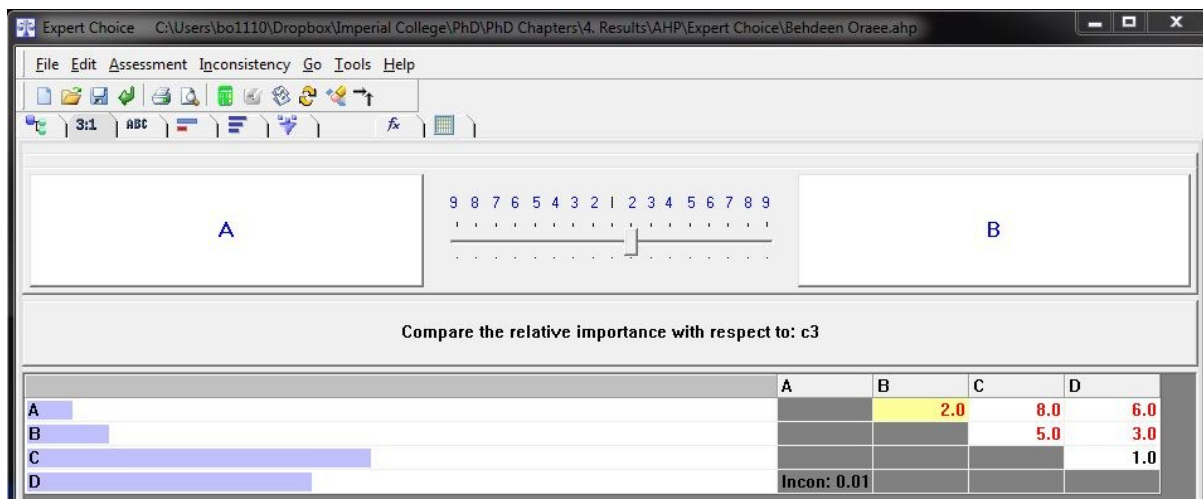


Figure 43, Comparison of alternatives with respect to “ c_3 ” using a numerical scale

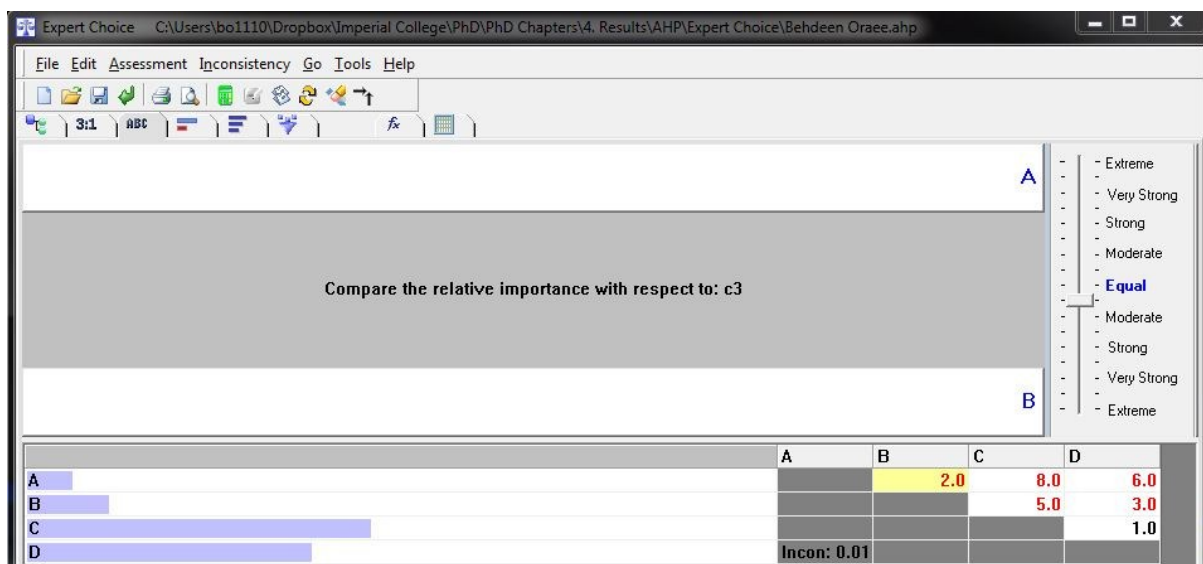


Figure 44, Comparison of alternatives with respect to “ c_3 ” using a linguistic scale

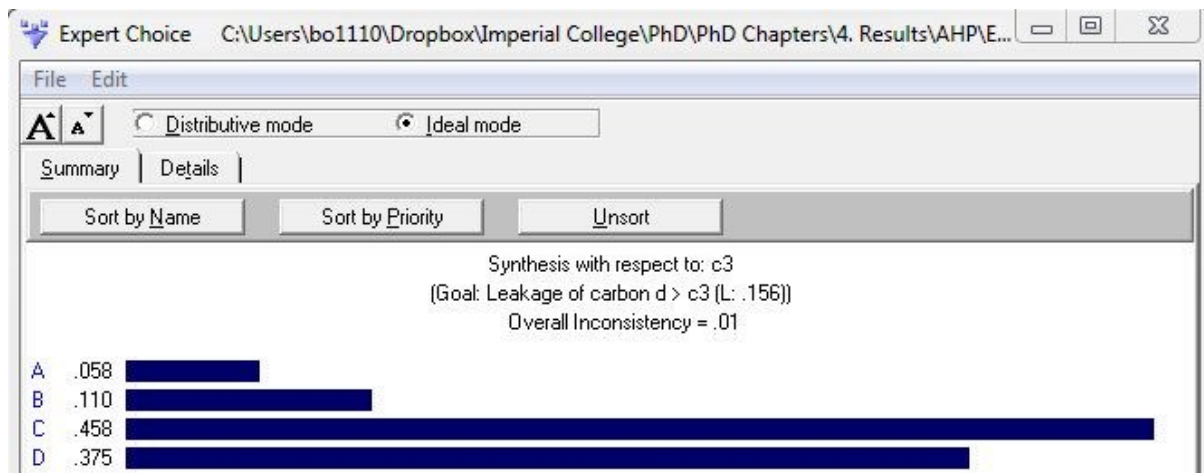


Figure 45, Final weight of alternatives with respect to “ c_3 ”

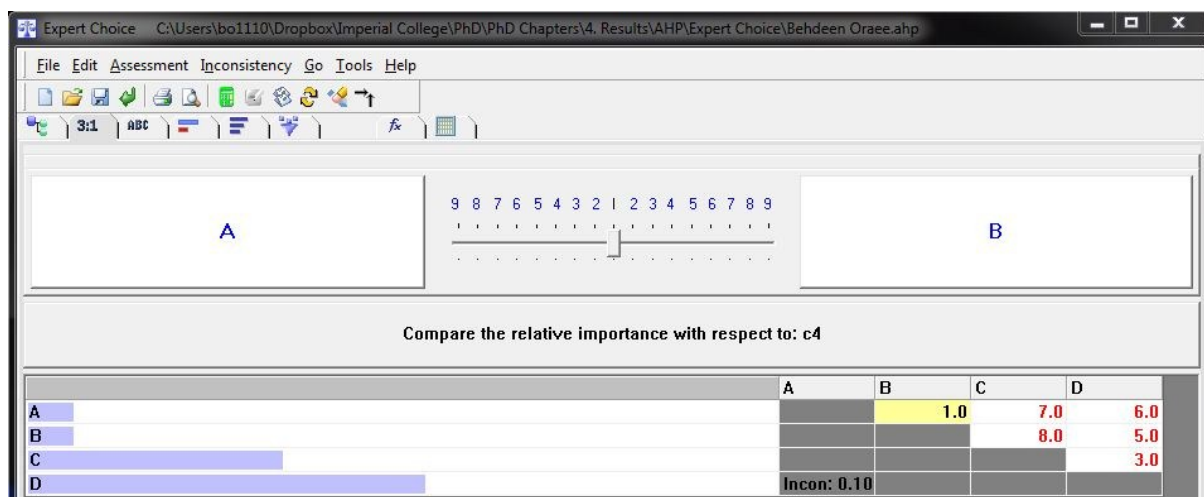


Figure 46, Comparison of alternatives with respect to “ c_4 ” using a numerical scale

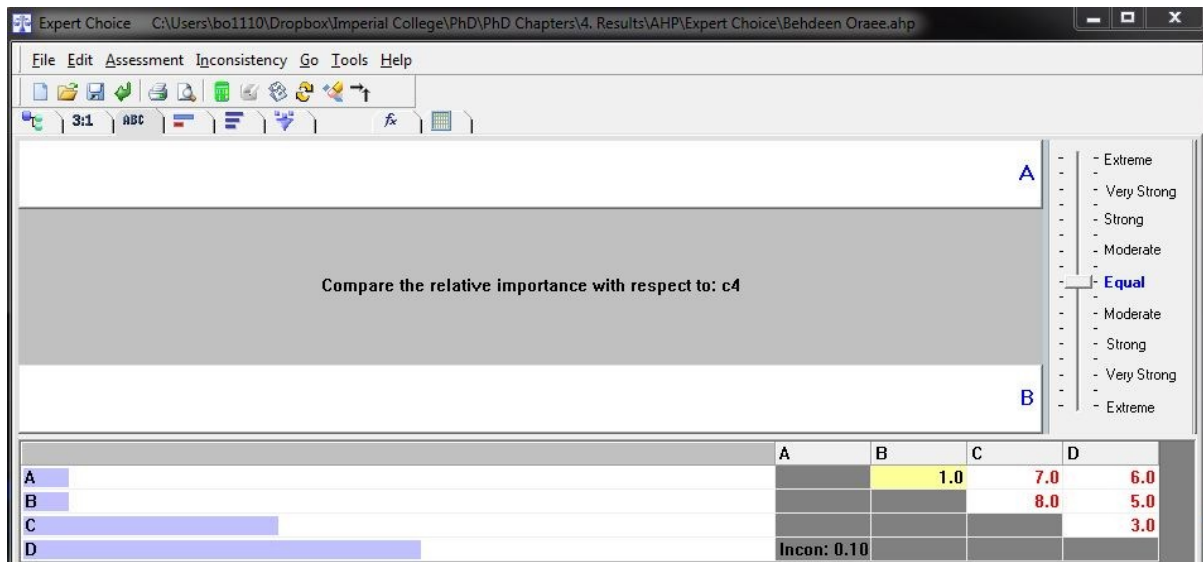


Figure 47, Comparison of alternatives with respect to “c₄” using a linguistic scale

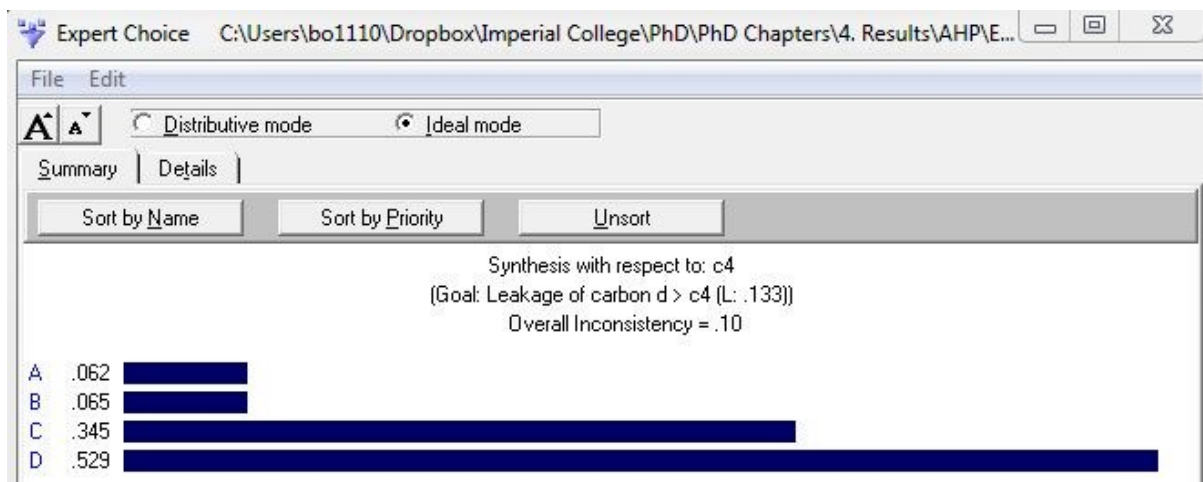


Figure 48, Final weight of alternatives with respect to “c₄”

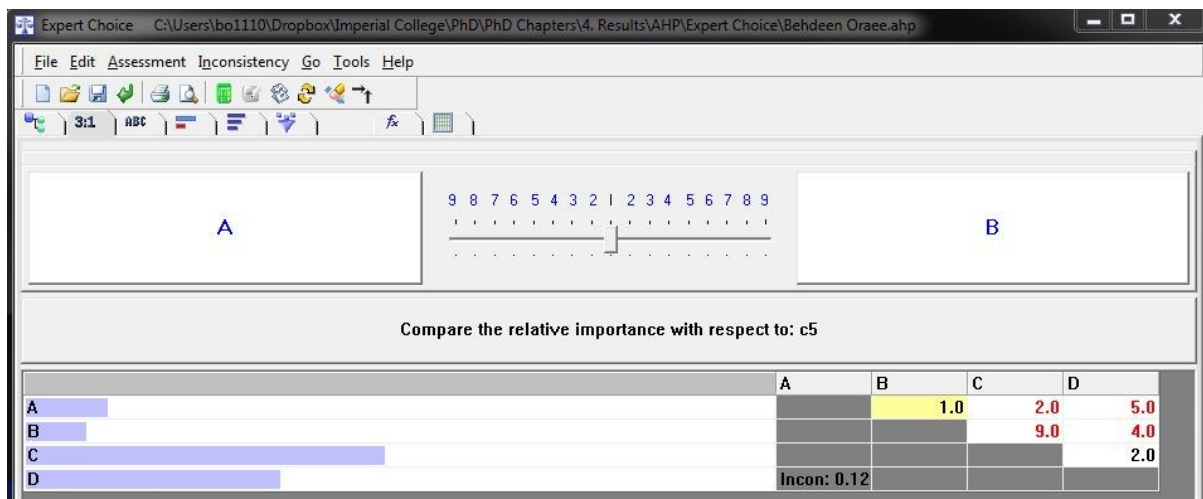


Figure 49, Comparison of alternatives with respect to “ c_5 ” using a numerical scale

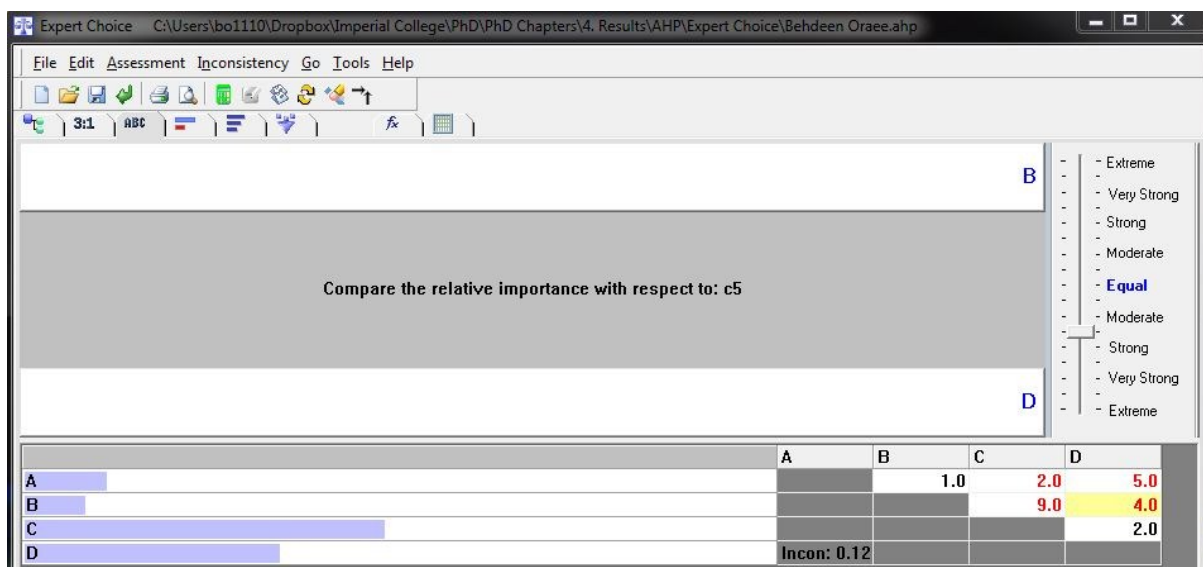


Figure 50, Comparison of alternatives with respect to “ c_5 ” using a linguistic scale

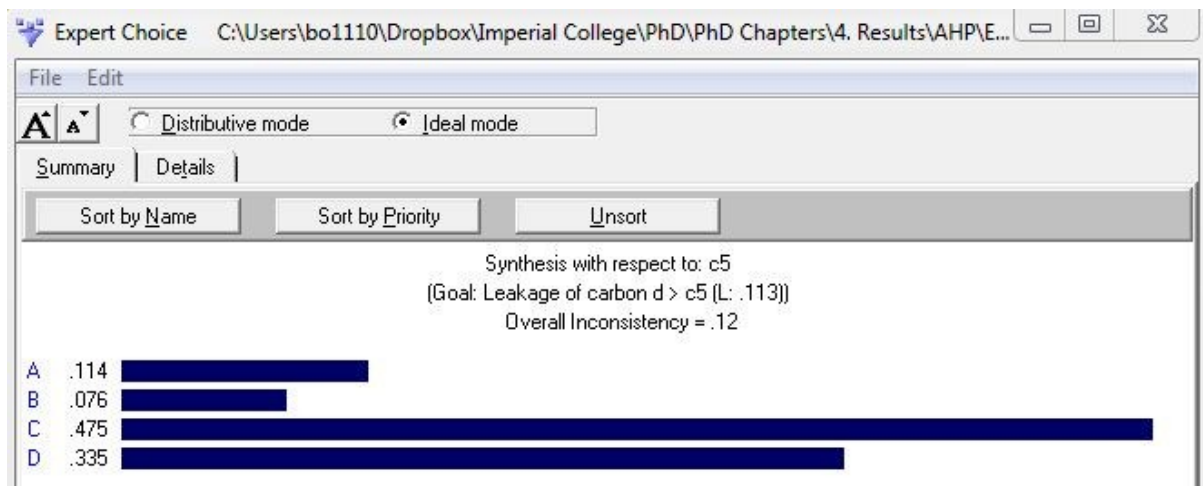


Figure 51, Final weight of alternatives with respect to “ c_5 ”

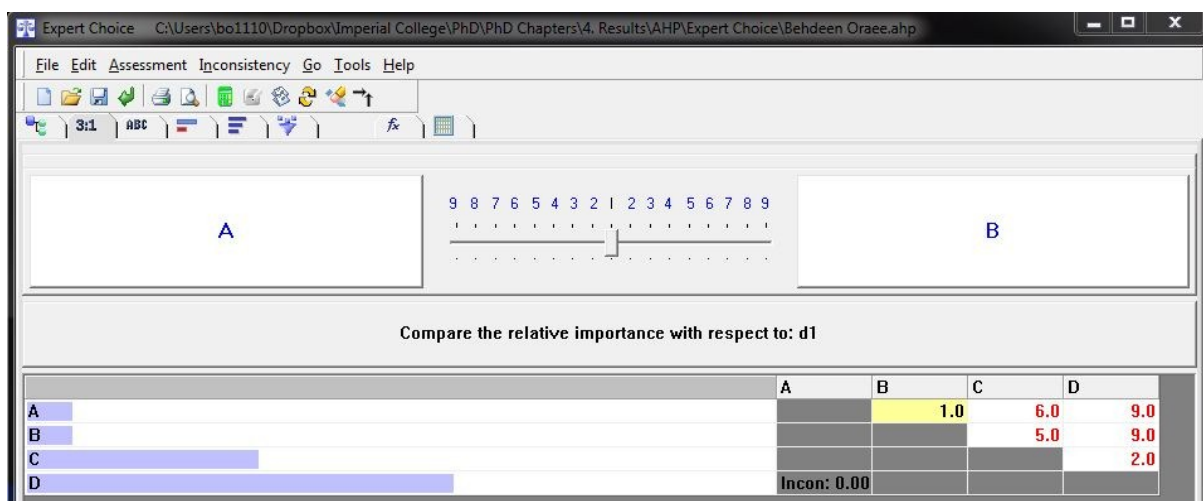


Figure 52, Comparison of alternatives with respect to “ d_1 ” using a numerical scale

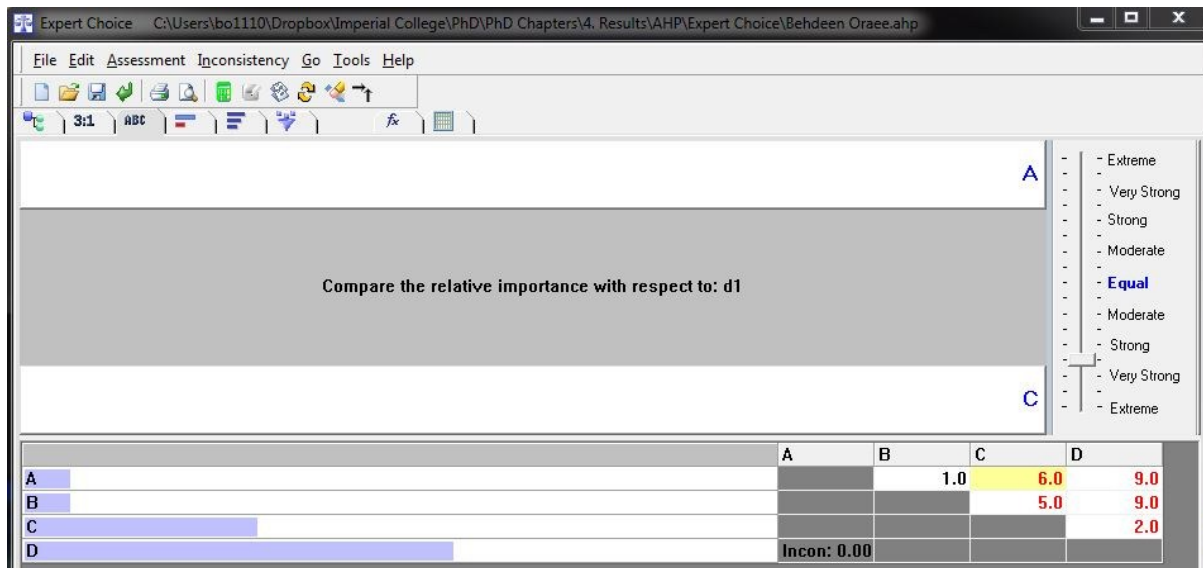


Figure 53, Comparison of alternatives with respect to “ d_1 ” using a linguistic scale

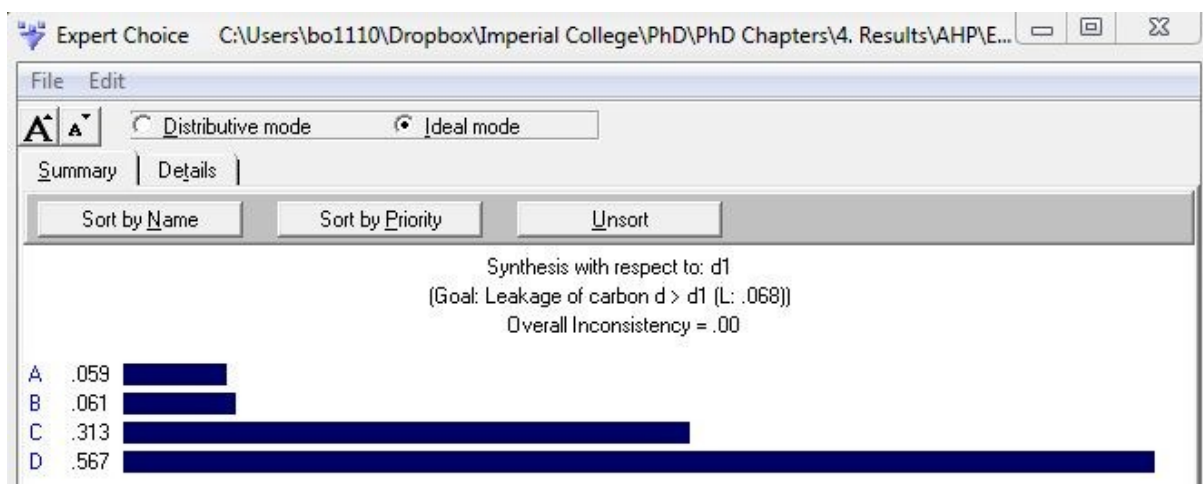


Figure 54, Final weight of alternatives with respect to “ d_1 ”

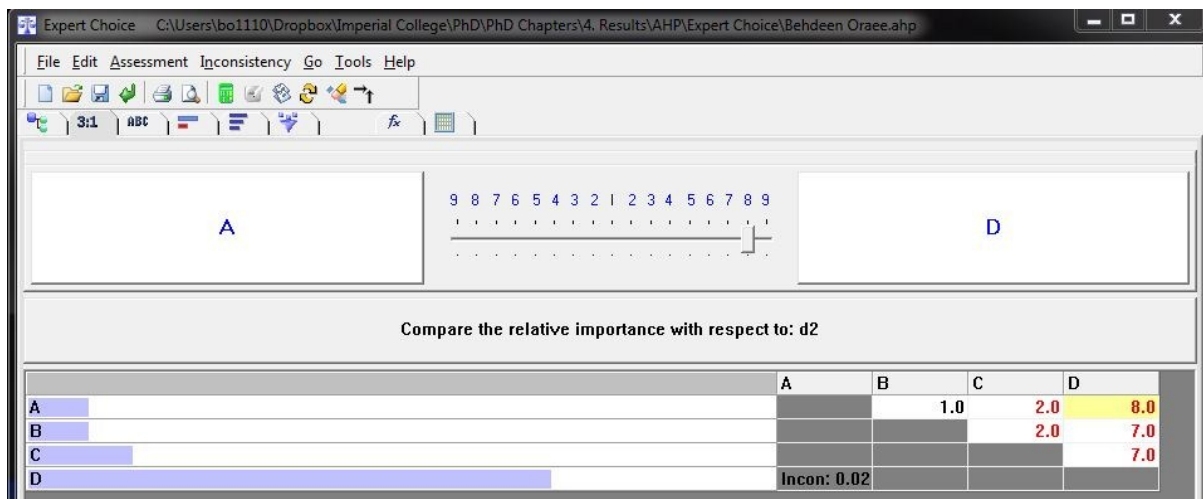


Figure 55, Comparison of alternatives with respect to “ d_2 ” using a numerical scale

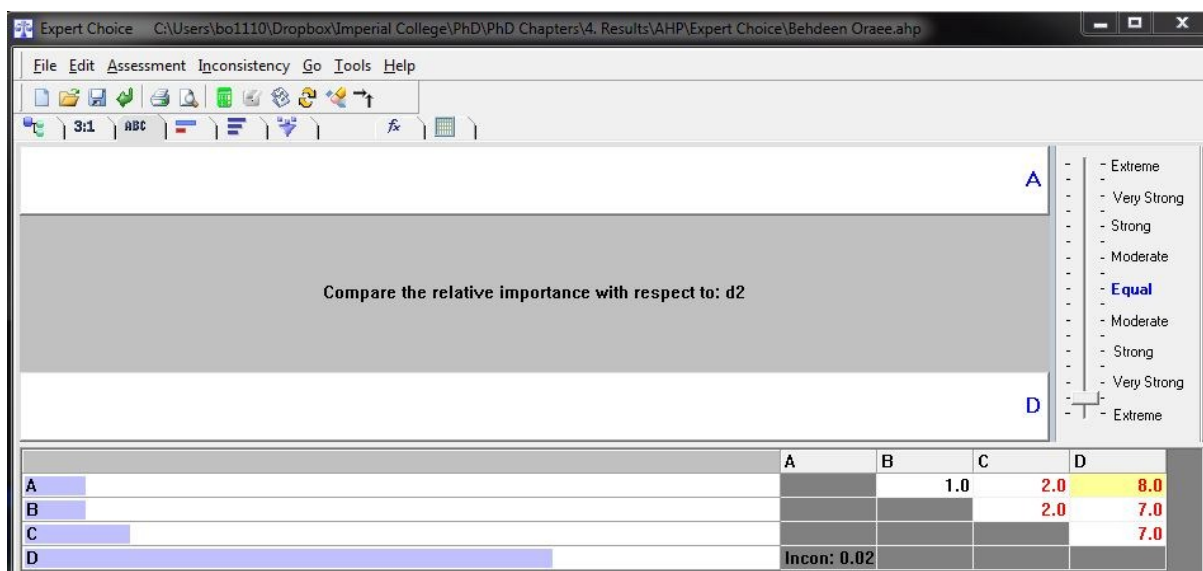


Figure 56, Comparison of alternatives with respect to “ d_2 ” using a linguistic scale

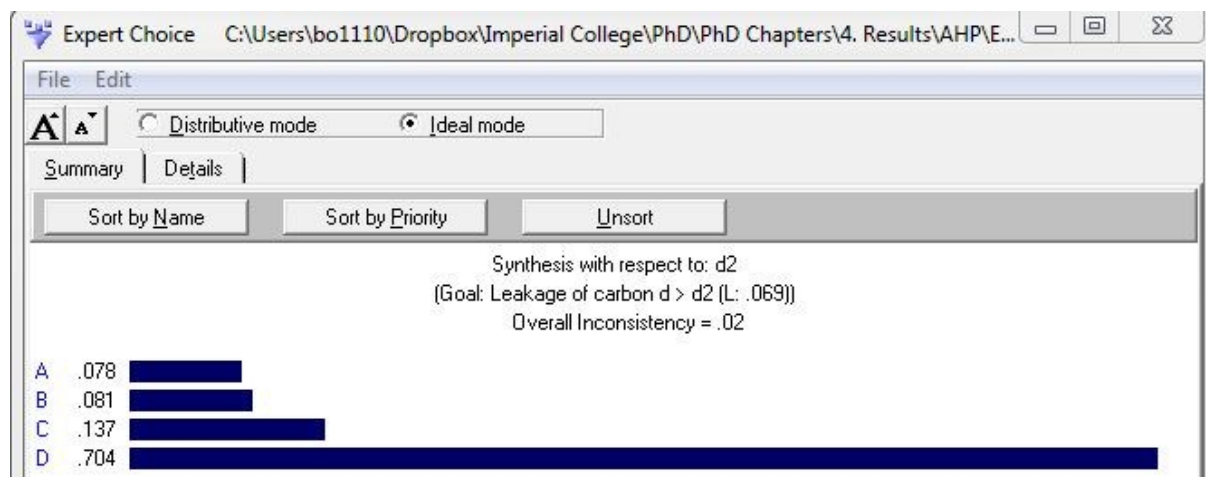


Figure 57, Final weight of alternatives with respect to “ d_2 ”

10.1.4 Calculation steps for the Fuzzy AHP method

Diffusion (possible initiation of other mechanisms) (a2)				
	A	B	C	D
A	(1,1,1)	(4,5,6)	(6,7,8)	(1,2,3)
B	(1/6,1/5,1/4)	(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)
C	(1/8,1/7,1/6)	(2,3,4)	(1,1,1)	(1,2,3)
D	(1/3,1/2,1)	(3,4,5)	(1/3,1/2,1)	(1,1,1)

Table 55, Fuzzy pair-wise comparison matrix for criteria a_2

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	4.00	6.00	1.00	12.00	22.41	0.027586207	0.33103
	2	1.00	5.00	7.00	2.00	15.00	28.93	0.034570747	0.51856
	3	1.00	6.00	8.00	3.00	18.00	36.25	0.044626255	0.80327
B	1	0.17	1.00	0.25	0.20	1.62		0.027586207	0.04460
	2	0.20	1.00	0.33	0.25	1.78		0.034570747	0.06165
	3	0.25	1.00	0.50	0.33	2.08		0.044626255	0.09297
C	1	0.13	2.00	1.00	1.00	4.13		0.027586207	0.11379
	2	0.14	3.00	1.00	2.00	6.14		0.034570747	0.21236
	3	0.17	4.00	1.00	3.00	8.17		0.044626255	0.36445
D	1	0.33	3.00	0.33	1.00	4.67		0.027586207	0.12874
	2	0.50	4.00	0.50	1.00	6.00		0.034570747	0.20742
	3	1.00	5.00	1.00	1.00	8.00		0.044626255	0.35701

Table 56, Showing the achieved TFNs for S_k s of criteria a_2

S_k			
	l	m	u
S1	0.3310	0.5186	0.8033
S2	0.0446	0.0617	0.0930
S3	0.1138	0.2124	0.3644
S4	0.1287	0.2074	0.3570

Table 57, TFN values of S_k for each alternative with respect to criteria a_2

s1 >= s2	1	s3 >= s1	0.098386
s1 >= s3	1	s3 >= s2	1
s1 >= s4	1	s3 >= s4	1
s2 >= s1	0	s4 >= s1	0.077053
s2 >= s3	0	s4 >= s2	1
s2 >= s4	0	s4 >= s3	0.980098

Table 58, Degree of possibility of different amounts of S_k for TFNs with respect to a_2

	S1	S2	S3	S4
S1	1.0000	1.0000	1.0000	1.0000
S2	0.0000	1.0000	0.0000	0.0000
S3	0.0984	1.0000	1.0000	1.0000
S4	0.0771	1.0000	0.9801	1.0000

Table 59, The achieved amounts of S_k for criteria a_2

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	1.0000	0.8507453
	min S2 >= S1, S3, S4	0.0000	0
	min S3 >= S1, S2, S4	0.0984	0.0837021
	min S4 >= S1, S2, S3	0.0771	0.0655526

Table 60, Calculation of the weights of the alternatives with respect to criteria a_2

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	1.0000	0.0000	0.0984	0.0771
w_i	0.8507	0.0000	0.0837	0.0656

Table 61, Vector of the weights of the alternatives with respect to criteria a_2

Fracturation of the caprock (b1)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(7,8,9)	(7,8,9)
B	(1,1,1)	(1,1,1)	(5,6,7)	(6,7,8)
C	(1/7,1/8,1/9)	(1/7,1/6,1/5)	(1,1,1)	(1/4,1/3,1/2)
D	(1/7,1/8,1/9)	(1/8,1/7,1/6)	(2,3,4)	(1,1,1)

Table 62, Fuzzy pair-wise comparison matrix for criteria b_1

TFNs			Sum of Rows			Sum	Inverse	S_k	
A	1	1.00	1.00	7.00	8.00	17.00	34.74	0.022657999	0.38519
	2	1.00	1.00	8.00	9.00	19.00	39.88	0.025075874	0.47644
	3	1.00	1.00	9.00	9.00	20.00	44.13	0.028785196	0.57570
B	1	1.00	1.00	5.00	6.00	13.00		0.022657999	0.29455
	2	1.00	1.00	6.00	7.00	15.00		0.025075874	0.37614
	3	1.00	1.00	7.00	8.00	17.00		0.028785196	0.48935
C	1	0.11	0.14	1.00	0.25	1.50		0.022657999	0.03408
	2	0.13	0.17	1.00	0.33	1.63		0.025075874	0.04075
	3	0.14	0.20	1.00	0.50	1.84		0.028785196	0.05305
D	1	0.11	0.13	2.00	1.00	3.24		0.022657999	0.07332
	2	0.11	0.14	3.00	1.00	4.25		0.025075874	0.10667
	3	0.13	0.17	4.00	1.00	5.29		0.028785196	0.15232

Table 63, Showing the achieved TFNs for S_k s of criteria b_1

S_k			
	l	m	u
S1	0.3852	0.4764	0.5757
S2	0.2946	0.3761	0.4893
S3	0.0341	0.0407	0.0530
S4	0.0733	0.1067	0.1523

Table 64, TFN values of S_k for each alternative with respect to criteria b_1

s1 >= s2	1	s3 >= s1	0
s1 >= s3	1	s3 >= s2	0
s1 >= s4	1	s3 >= s4	0
s2 >= s1	0.509436	s4 >= s1	0
s2 >= s3	1	s4 >= s2	0
s2 >= s4	1	s4 >= s3	1

Table 65, Degree of possibility of different amounts of S_k for TFNs with respect to b_1

	S1	S2	S3	S4
S1	1.0000	1.0000	1.0000	1.0000
S2	0.5094	1.0000	1.0000	1.0000
S3	0.0000	0.0000	1.0000	0.0000
S4	0.0000	0.0000	1.0000	1.0000

Table 66, The achieved amounts of S_k for criteria b_1

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	1.0000	0.66249892
	min S2 >= S1, S3, S4	0.5094	0.33750108
	min S3 >= S1, S2, S4	0.0000	0
	min S4 >= S1, S2, S3	0.0000	0

Table 67, Calculation of the weights of the alternatives with respect to criteria b_1

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	1.0000	0.0000	0.0984	0.0771
w_i	0.8507	0.0000	0.0837	0.0656

Table 68, Vector of the weights of the alternatives with respect to criteria b_1

Non-permeable rock that becomes permeable (b2)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/5,1/4,1/3)	(1/4,1/3,1/2)
B	(1,1,1)	(1,1,1)	(7,8,9)	(7,8,9)
C	(3,4,5)	(1/7,1/8,1/9)	(1,1,1)	(1,1,1)
D	(2,3,4)	(1/7,1/8,1/9)	(1,1,1)	(1,1,1)

Table 69, Fuzzy pair-wise comparison matrix for criteria b_2

TFNs			Sum of Rows				Sum	Inverse	S_k
A	1	1.00	1.00	0.20	0.25	2.45	28.67	0.02769992	0.06786
	2	1.00	1.00	0.25	0.33	2.58	32.82	0.03046974	0.07871
	3	1.00	1.00	0.33	0.50	2.83	36.10	0.03487696	0.09882
B	1	1.00	1.00	8.00	7.00	17.00		0.02769992	0.47090
	2	1.00	1.00	9.00	8.00	19.00		0.03046974	0.57893
	3	1.00	1.00	9.00	9.00	20.00		0.03487696	0.69754
C	1	3.00	0.11	1.00	1.00	5.11		0.02769992	0.14158
	2	4.00	0.11	1.00	1.00	6.11		0.03046974	0.18620
	3	5.00	0.13	1.00	1.00	7.13		0.03487696	0.24850
D	1	2.00	0.11	1.00	1.00	4.11		0.02769992	0.11388
	2	3.00	0.13	1.00	1.00	5.13		0.03046974	0.15616
	3	4.00	0.14	1.00	1.00	6.14		0.03487696	0.21424

Table 70, Showing the achieved TFNs for S_k s of criteria b_2

S_k			
	l	m	u
S1	0.0679	0.0787	0.0988
S2	0.4709	0.5789	0.6975
S3	0.1416	0.1862	0.2485
S4	0.1139	0.1562	0.2142

Table 71, TFN values of S_k for each alternative with respect to criteria b_2

s1 >= s2	0	s3 >= s1	1
s1 >= s3	0	s3 >= s2	0
s1 >= s4	0	s3 >= s4	1
s2 >= s1	1	s4 >= s1	1
s2 >= s3	1	s4 >= s2	0
s2 >= s4	1	s4 >= s3	0.70747191

Table 72, Degree of possibility of different amounts of S_k for TFNs with respect to b_2

	S1	S2	S3	S4
S1	1.0000	0.0000	0.0000	0.0000
S2	1.0000	1.0000	1.0000	1.0000
S3	1.0000	0.0000	1.0000	1.0000
S4	1.0000	0.0000	0.7075	1.0000

Table 73, The achieved amounts of S_k for criteria b_2

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	0.0000	0
	min S2 >= S1, S3, S4	1.0000	1
	min S3 >= S1, S2, S4	0.0000	0
	min S4 >= S1, S2, S3	0.0000	0

Table 74, Calculation of the weights of the alternatives with respect to criteria b_2

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	1.0000	0.0000	0.0000
w_i	0.0000	1.0000	0.0000	0.0000

Table 75, Vector of the weights of the alternatives with respect to criteria b_2

Pre-existing fracture of the caprock (b3)				
	A	B	C	D
A	(1,1,1)	(7,8,9)	(7,8,9)	(7,8,9)
B	(1/7,1/8,1/9)	(1,1,1)	(5,6,7)	(6,7,8)
C	(1/7,1/8,1/9)	(1/7,1/6,1/5)	(1,1,1)	(1,1,1)
D	(1/7,1/8,1/9)	(1/8,1/7,1/6)	(1,1,1)	(1,1,1)

Table 76, Fuzzy pair-wise comparison matrix for criteria b_3

TFNs			Sum of Rows			Sum		Inverse	S_k
A	1	1.00	8.00	7.00	7.00	23.00	39.60	0.02050131	0.47153
	2	1.00	9.00	8.00	8.00	26.00	44.67	0.02238607	0.58204
	3	1.00	9.00	9.00	9.00	28.00	48.78	0.02525177	0.70705
B	1	0.11	1.00	5.00	6.00	12.11		0.02050131	0.24829
	2	0.11	1.00	6.00	7.00	14.11		0.02238607	0.31589
	3	0.13	1.00	7.00	8.00	16.13		0.02525177	0.40718
C	1	0.11	0.14	1.00	1.00	2.25		0.02050131	0.04621
	2	0.13	0.17	1.00	1.00	2.29		0.02238607	0.05130
	3	0.14	0.20	1.00	1.00	2.34		0.02525177	0.05916
D	1	0.11	0.13	1.00	1.00	2.24		0.02050131	0.04584
	2	0.13	0.14	1.00	1.00	2.27		0.02238607	0.05077
	3	0.14	0.17	1.00	1.00	2.31		0.02525177	0.05832

Table 77, Showing the achieved TFNs for S_k s of criteria b_3

S_k			
	l	m	u
S1	0.4715	0.5820	0.7070
S2	0.2483	0.3159	0.4072
S3	0.0462	0.0513	0.0592
S4	0.0458	0.0508	0.0583

Table 78, TFN values of S_k for each alternative with respect to criteria b_3

s1 >= s2	1	s3 >= s1	0
s1 >= s3	1	s3 >= s2	0
s1 >= s4	1	s3 >= s4	1
s2 >= s1	0	s4 >= s1	0
s2 >= s3	1	s4 >= s2	0
s2 >= s4	1	s4 >= s3	0.957843

Table 79, Degree of possibility of different amounts of S_k for TFNs with respect to b_3

	S1	S2	S3	S4
S1	1.0000	1.0000	1.0000	1.0000
S2	0.0000	1.0000	1.0000	1.0000
S3	0.0000	0.0000	1.0000	1.0000
S4	0.0000	0.0000	0.9578	1.0000

Table 80, The achieved amounts of S_k for criteria b_3

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	1.0000	1
	min S2 >= S1, S3, S4	0.0000	0
	min S3 >= S1, S2, S4	0.0000	0
	min S4 >= S1, S2, S3	0.0000	0

Table 81, Calculation of the weights of the alternatives with respect to criteria b_3

Vector of weight, w' (x_i), and Vector of normalised attributes, w_i				
w' (x_i)	1.0000	0.0000	0.0000	0.0000
w_i	1.0000	0.0000	0.0000	0.0000

Table 82, Vector of the weights of the alternatives with respect to criteria b_3

Vertical migration through fractures in cement (c1)				
	A	B	C	D
A	(1,1,1)	(1/4,1/3,1/2)	(1/7,1/8,1/9)	(1/8,1/7,1/6)
B	(2,3,4)	(1,1,1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)
C	(7,8,9)	(4,5,6)	(1,1,1)	(1/3,1/2,1)
D	(6,7,8)	(2,3,4)	(1,2,3)	(1,1,1)

Table 83, Fuzzy pair-wise comparison matrix for criteria c_1

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	0.25	0.11	0.13	1.49	28.24	0.02466598	0.03666
	2	1.00	0.33	0.11	0.14	1.59	34.62	0.02888451	0.04585
	3	1.00	0.50	0.13	0.17	1.79	40.54	0.03541564	0.06345
B	1	2.00	1.00	0.17	0.25	3.42		0.02466598	0.08428
	2	3.00	1.00	0.20	0.33	4.53		0.02888451	0.13094
	3	4.00	1.00	0.25	0.50	5.75		0.03541564	0.20364
C	1	8.00	4.00	1.00	0.33	13.33		0.02466598	0.32888
	2	9.00	5.00	1.00	0.50	15.50		0.02888451	0.44771
	3	9.00	6.00	1.00	1.00	17.00		0.03541564	0.60207
D	1	6.00	2.00	1.00	1.00	10.00		0.02466598	0.24666
	2	7.00	3.00	2.00	1.00	13.00		0.02888451	0.37550
	3	8.00	4.00	3.00	1.00	16.00		0.03541564	0.56665

Table 84, Showing the achieved TFNs for S_k s of criteria c_1

S_k			
	l	m	u
S1	0.0367	0.0458	0.0635
S2	0.0843	0.1309	0.2036
S3	0.3289	0.4477	0.6021
S4	0.2467	0.3755	0.5667

Table 85, TFN values of S_k for each alternative with respect to criteria c_1

s1 $\geq$ s2	0	s3 $\geq$ s1	1
s1 $\geq$ s3	0	s3 $\geq$ s2	1
s1 $\geq$ s4	0	s3 $\geq$ s4	1
s2 $\geq$ s1	1	s4 $\geq$ s1	1
s2 $\geq$ s3	0	s4 $\geq$ s2	1
s2 $\geq$ s4	0	s4 $\geq$ s3	0.767046734

Table 86, Degree of possibility of different amounts of S_k for TFNs with respect to c_1

	S1	S2	S3	S4
S1	1.0000	0.0000	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.7670	1.0000

Table 87, The achieved amounts of S_k for criteria c_1

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 $\geq$ S2, S3, S4	0.0000	0
	min S2 $\geq$ S1, S3, S4	0.0000	0
	min S3 $\geq$ S1, S2, S4	1.0000	0.56591599
	min S4 $\geq$ S1, S2, S3	0.7670	0.43408401

Table 88, Calculation of the weights of the alternatives with respect to criteria c_1

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	1.0000	0.7670
w_i	0.0000	0.0000	0.5659	0.4341

Table 89, Vector of the weights of the alternatives with respect to criteria c_1

Vertical migration at cement/casing interface (c2)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/7,1/8,1/9)	(1/6,1/5,1/4)
B	(1,1,1)	(1,1,1)	(1/8,1/7,1/6)	(1/5,1/4,1/3)
C	(7,8,9)	(6,7,8)	(1,1,1)	(1,2,3)
D	(4,5,6)	(3,4,5)	(1/3,1/2,1)	(1,1,1)

Table 90, Fuzzy pair-wise comparison matrix for criteria c_2

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	1.00	0.11	0.17	2.28	27.94	0.0257	0.05854
	2	1.00	1.00	0.13	0.20	2.33	33.22	0.0301	0.07013
	3	1.00	1.00	0.14	0.25	2.39	38.89	0.0358	0.08556
B	1	1.00	1.00	0.13	0.20	2.33		0.0257	0.05978
	2	1.00	1.00	0.14	0.25	2.39		0.0301	0.07202
	3	1.00	1.00	0.17	0.33	2.50		0.0358	0.08949
C	1	7.00	6.00	1.00	1.00	15.00		0.0257	0.38570
	2	8.00	7.00	1.00	2.00	18.00		0.0301	0.54180
	3	9.00	8.00	1.00	3.00	21.00		0.0358	0.75175
D	1	4.00	3.00	0.33	1.00	8.33		0.0257	0.21428
	2	5.00	4.00	0.50	1.00	10.50		0.0301	0.31605
	3	6.00	5.00	1.00	1.00	13.00		0.0358	0.46537

Table 91, Showing the achieved TFNs for S_k s of criteria c_2

S_k			
	l	m	u
S1	0.0585	0.0701	0.0856
S2	0.0598	0.0720	0.0895
S3	0.3857	0.5418	0.7517
S4	0.2143	0.3160	0.4654

Table 92, TFN values of S_k for each alternative with respect to criteria c_2

s1 >= s2	0.93160775	s3 >= s1	1
s1 >= s3	0	s3 >= s2	1
s1 >= s4	0	s3 >= s4	1
s2 >= s1	1	s4 >= s1	1
s2 >= s3	0	s4 >= s2	1
s2 >= s4	0	s4 >= s3	0.26083793

Table 93, Degree of possibility of different amounts of S_k for TFNs with respect to c_2

	S1	S2	S3	S4
S1	1.0000	0.9316	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.2608	1.0000

Table 94, The achieved amounts of S_k for criteria c_2

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	0.0000	0
	min S2 >= S1, S3, S4	0.0000	0
	min S3 >= S1, S2, S4	1.0000	0.7931233
	min S4 >= S1, S2, S3	0.2608	0.2068767

Table 95, Calculation of the weights of the alternatives with respect to criteria c_2

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	1.0000	0.2608
w_i	0.0000	0.0000	0.7931	0.2069

Table 96, Vector of the weights of the alternatives with respect to criteria c_2

Vertical migration at cement/rock interface (c3)				
	A	B	C	D
A	(1,1,1)	(1/3,1/2,1)	(1/7,1/8,1/9)	(1/7,1/6,1/5)
B	(1,2,3)	(1,1,1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)
C	(7,8,9)	(4,5,6)	(1,1,1)	(1,1,1)
D	(5,6,7)	(2,3,4)	(1,1,1)	(1,1,1)

Table 97, Fuzzy pair-wise comparison matrix for criteria c_3

TFNs			Sum of Rows				Sum	Inverse	S_k
A	1	1.00	0.33	0.11	0.14	1.59	26.00	0.0269614	0.04277
	2	1.00	0.50	0.13	0.17	1.80	31.33	0.0319183	0.05735
	3	1.00	1.00	0.14	0.20	2.34	37.09	0.0384573	0.08999
B	1	1.00	1.00	0.17	0.25	2.42		0.0269614	0.06516
	2	2.00	1.00	0.20	0.33	3.53		0.0319183	0.11278
	3	3.00	1.00	0.25	0.50	4.75		0.0384573	0.18267
C	1	7.00	4.00	1.00	1.00	13.00		0.0269614	0.35050
	2	8.00	5.00	1.00	1.00	15.00		0.0319183	0.47877
	3	9.00	6.00	1.00	1.00	17.00		0.0384573	0.65377
D	1	5.00	2.00	1.00	1.00	9.00		0.0269614	0.24265
	2	6.00	3.00	1.00	1.00	11.00		0.0319183	0.35110
	3	7.00	4.00	1.00	1.00	13.00		0.0384573	0.49995

Table 98, Showing the achieved TFNs for S_k s of criteria c_3

S_k			
	l	m	u
S1	0.0428	0.0573	0.0900
S2	0.0652	0.1128	0.1827
S3	0.3505	0.4788	0.6538
S4	0.2427	0.3511	0.4999

Table 99, TFN values of S_k for each alternative with respect to criteria c_3

s1 >= s2	0.30939231	s3 >= s1	1
s1 >= s3	0	s3 >= s2	1
s1 >= s4	0	s3 >= s4	1
s2 >= s1	1	s4 >= s1	1
s2 >= s3	0	s4 >= s2	1
s2 >= s4	0	s4 >= s3	0.539285

Table 100, Degree of possibility of different amounts of S_k for TFNs with respect to c_3

	S1	S2	S3	S4
S1	1.0000	0.3094	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.5393	1.0000

Table 101, The achieved amounts of S_k for criteria c_3

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 >= S2, S3, S4	0.0000	0
	min S2 >= S1, S3, S4	0.0000	0
	min S3 >= S1, S2, S4	1.0000	0.64965239
	min S4 >= S1, S2, S3	0.5393	0.35034761

Table 102, Calculation of the weights of the alternatives with respect to criteria c_3

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	1.0000	0.5393
w_i	0.0000	0.0000	0.6497	0.3503

Table 103, Vector of the weights of the alternatives with respect to criteria c_3

Vertical migration through EDZ (c4)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/8,1/7,1/6)	(1/7,1/6,1/5)
B	(1,1,1)	(1,1,1)	(1/7,1/8,1/9)	(1/6,1/5,1/4)
C	(6,7,8)	(7,8,9)	(1,1,1)	(1/4,1/3,1/2)
D	(5,6,7)	(4,5,6)	(2,3,4)	(1,1,1)

Table 104, Fuzzy pair-wise comparison matrix for criteria c_4

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	1.00	0.13	0.14	2.27	30.79	0.02423851	0.05497
	2	1.00	1.00	0.14	0.17	2.31	35.97	0.02779874	0.06420
	3	1.00	1.00	0.17	0.20	2.37	41.26	0.03247331	0.07685
B	1	1.00	1.00	0.11	0.17	2.28		0.02423851	0.05518
	2	1.00	1.00	0.13	0.20	2.33		0.02779874	0.06477
	3	1.00	1.00	0.14	0.25	2.39		0.03247331	0.07761
C	1	6.00	7.00	1.00	0.25	14.25		0.02423851	0.34540
	2	7.00	8.00	1.00	0.33	16.33		0.02779874	0.45405
	3	8.00	9.00	1.00	0.50	18.50		0.03247331	0.60076
D	1	5.00	4.00	2.00	1.00	12.00		0.02423851	0.29086
	2	6.00	5.00	3.00	1.00	15.00		0.02779874	0.41698
	3	7.00	6.00	4.00	1.00	18.00		0.03247331	0.58452

Table 105, Showing the achieved TFNs for S_k s of criteria c_4

S_k			
	l	m	u
S1	0.0550	0.0642	0.0769
S2	0.0552	0.0648	0.0776
S3	0.3454	0.4540	0.6008
S4	0.2909	0.4170	0.5845

Table 106, TFN values of S_k for each alternative with respect to criteria c_4

s1 $\geq$ s2	0.974405583	s3 $\geq$ s1	1
s1 $\geq$ s3	0	s3 $\geq$ s2	1
s1 $\geq$ s4	0	s3 $\geq$ s4	1
s2 $\geq$ s1	1	s4 $\geq$ s1	1
s2 $\geq$ s3	0	s4 $\geq$ s2	1
s2 $\geq$ s4	0	s4 $\geq$ s3	0.86579691

Table 107, Degree of possibility of different amounts of S_k for TFNs with respect to c_4

	S1	S2	S3	S4
S1	1.0000	0.9744	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.8658	1.0000

Table 108, The achieved amounts of S_k for criteria c_4

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 $\geq$ S2, S3, S4	0.0000	0
	min S2 $\geq$ S1, S3, S4	0.0000	0
	min S3 $\geq$ S1, S2, S4	1.0000	0.53596401
	min S4 $\geq$ S1, S2, S3	0.8658	0.46403599

Table 109, Calculation of the weights of the alternatives with respect to criteria c_4

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	1.0000	0.8658
w_i	0.0000	0.0000	0.5360	0.4640

Table 110, Vector of the weights of the alternatives with respect to criteria c_4

Migration through cement matrix (cement wall) (c5)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/3,1/2,1)	(1/6,1/5,1/4)
B	(1,1,1)	(1,1,1)	(1/7,1/8,1/9)	(1/5,1/4,1/3)
C	(1,2,3)	(7,8,9)	(1,1,1)	(1,2,3)
D	(4,5,6)	(3,4,5)	(1/3,1/2,1)	(1,1,1)

Table 111, Fuzzy pair-wise comparison matrix for criteria c_5

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	1.00	0.33	0.17	2.50	24.14	0.02881152	0.07203
	2	1.00	1.00	0.50	0.20	2.70	29.56	0.03382823	0.09134
	3	1.00	1.00	1.00	0.25	3.25	34.71	0.0414174	0.13461
B	1	1.00	1.00	0.11	0.20	2.31		0.02881152	0.06659
	2	1.00	1.00	0.11	0.25	2.36		0.03382823	0.07987
	3	1.00	1.00	0.13	0.33	2.46		0.0414174	0.10182
C	1	1.00	8.00	1.00	1.00	11.00		0.02881152	0.31693
	2	2.00	9.00	1.00	2.00	14.00		0.03382823	0.47360
	3	3.00	9.00	1.00	3.00	16.00		0.0414174	0.66268
D	1	4.00	3.00	0.33	1.00	8.33		0.02881152	0.24010
	2	5.00	4.00	0.50	1.00	10.50		0.03382823	0.35520
	3	6.00	5.00	1.00	1.00	13.00		0.0414174	0.53843

Table 112, Showing the achieved TFNs for S_k s of criteria c_5

S_k			
	l	m	u
S1	0.0720	0.0913	0.1346
S2	0.0666	0.0799	0.1018
S3	0.3169	0.4736	0.6627
S4	0.2401	0.3552	0.5384

Table 113, TFN values of S_k for each alternative with respect to criteria c_5

s1 $\geq$ s2	1	s3 $\geq$ s1	1
s1 $\geq$ s3	0	s3 $\geq$ s2	1
s1 $\geq$ s4	0	s3 $\geq$ s4	1
s2 $\geq$ s1	0.72210455	s4 $\geq$ s1	1
s2 $\geq$ s3	0	s4 $\geq$ s2	1
s2 $\geq$ s4	0	s4 $\geq$ s3	0.651663912

Table 114, Degree of possibility of different amounts of S_k for TFNs with respect to c_5

	S1	S2	S3	S4
S1	1.0000	1.0000	0.0000	0.0000
S2	0.7221	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.6517	1.0000

Table 115, The achieved amounts of S_k for criteria c_5

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 $\geq$ S2, S3, S4	0.0000	0
	min S2 $\geq$ S1, S3, S4	0.0000	0
	min S3 $\geq$ S1, S2, S4	1.0000	0.60545005
	min S4 $\geq$ S1, S2, S3	0.6517	0.39454995

Table 116, Calculation of the weights of the alternatives with respect to criteria c_5

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	1.0000	0.6517
w_i	0.0000	0.0000	0.6055	0.3945

Table 117, Vector of the weights of the alternatives with respect to criteria c_5

Leakage through a monitoring well (d1)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/7,1/6,1/5)	(1/7,1/8,1/9)
B	(1,1,1)	(1,1,1)	(1/6,1/5,1/4)	(1/7,1/8,1/9)
C	(5,6,7)	(4,5,6)	(1,1,1)	(1/3,1/2,1)
D	(7,8,9)	(7,8,9)	(1,2,3)	(1,1,1)

Table 118, Fuzzy pair-wise comparison matrix for criteria d_1

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	1.00	0.14	0.11	2.25	32.87	0.024	0.05405
	2	1.00	1.00	0.17	0.11	2.28	38.09	0.0263	0.05980
	3	1.00	1.00	0.20	0.13	2.33	41.70	0.0304	0.07074
B	1	1.00	1.00	0.17	0.11	2.28		0.024	0.05462
	2	1.00	1.00	0.20	0.11	2.31		0.0263	0.06068
	3	1.00	1.00	0.25	0.13	2.38		0.0304	0.07227
C	1	5.00	4.00	1.00	0.33	10.33		0.024	0.24780
	2	6.00	5.00	1.00	0.50	12.50		0.0263	0.32818
	3	7.00	6.00	1.00	1.00	15.00		0.0304	0.45641
D	1	8.00	8.00	1.00	1.00	18.00		0.024	0.43165
	2	9.00	9.00	2.00	1.00	21.00		0.0263	0.55134
	3	9.00	9.00	3.00	1.00	22.00		0.0304	0.66940

Table 119, Showing the achieved TFNs for S_k s of criteria d_1

S_k			
	l	m	u
S1	0.0541	0.0598	0.0707
S2	0.0546	0.0607	0.0723
S3	0.2478	0.3282	0.4564
S4	0.4317	0.5513	0.6694

Table 120, TFN values of S_k for each alternative with respect to criteria d_1

s1 $\geq$ s2	0.94850859	s3 $\geq$ s1	1
s1 $\geq$ s3	0	s3 $\geq$ s2	1
s1 $\geq$ s4	0	s3 $\geq$ s4	0.09985849
s2 $\geq$ s1	1	s4 $\geq$ s1	1
s2 $\geq$ s3	0	s4 $\geq$ s2	1
s2 $\geq$ s4	0	s4 $\geq$ s3	1

Table 121, Degree of possibility of different amounts of S_k for TFNs with respect to d_1

	S1	S2	S3	S4
S1	1.0000	0.9485	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	0.0999
S4	1.0000	1.0000	1.0000	1.0000

Table 122, The achieved amounts of S_k for criteria d_1

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 $\geq$ S2, S3, S4	0.0000	0
	min S2 $\geq$ S1, S3, S4	0.0000	0
	min S3 $\geq$ S1, S2, S4	0.0999	0.0907921
	min S4 $\geq$ S1, S2, S3	1.0000	0.9092079

Table 123, Calculation of the weights of the alternatives with respect to criteria d_1

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	0.0999	1.0000
w_i	0.0000	0.0000	0.0908	0.9092

Table 124, Vector of the weights of the alternatives with respect to criteria d_1

Leakage through an exterior well (d2)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/3,1/2,1)	(1/7,1/8,1/9)
B	(1,1,1)	(1,1,1)	(1/3,1/2,1)	(1/8,1/7,1/6)
C	(1,2,3)	(1,2,3)	(1,1,1)	(1/8,1/7,1/6)
D	(7,8,9)	(6,7,8)	(6,7,8)	(1,1,1)

Table 125, Fuzzy pair-wise comparison matrix for criteria d_2

TFNs		Sum of Rows					Sum	Inverse	S_k
A	1	1.00	1.00	0.33	0.11	2.44	28.03	0.025333559	0.06190
	2	1.00	1.00	0.50	0.13	2.63	33.42	0.02992604	0.07871
	3	1.00	1.00	1.00	0.14	3.14	39.47	0.035680304	0.11204
B	1	1.00	1.00	0.33	0.13	2.46		0.025333559	0.06228
	2	1.00	1.00	0.50	0.14	2.64		0.02992604	0.07909
	3	1.00	1.00	1.00	0.17	3.17		0.035680304	0.11299
C	1	1.00	1.00	1.00	0.13	3.13		0.025333559	0.07917
	2	2.00	2.00	1.00	0.14	5.14		0.02992604	0.15391
	3	3.00	3.00	1.00	0.17	7.17		0.035680304	0.25571
D	1	7.00	6.00	6.00	1.00	20.00		0.025333559	0.50667
	2	8.00	7.00	7.00	1.00	23.00		0.02992604	0.68830
	3	9.00	8.00	8.00	1.00	26.00		0.035680304	0.92769

Table 126, Showing the achieved TFNs for S_k s of criteria d_2

S_k			
	l	m	u
S1	0.0619	0.0787	0.1120
S2	0.0623	0.0791	0.1130
S3	0.0792	0.1539	0.2557
S4	0.5067	0.6883	0.9277

Table 127, TFN values of S_k for each alternative with respect to criteria d_2

s1 $\geq$ s2	0.99232662	s3 $\geq$ s1	1
s1 $\geq$ s3	0.30414728	s3 $\geq$ s2	1
s1 $\geq$ s4	0	s3 $\geq$ s4	0
s2 $\geq$ s1	1	s4 $\geq$ s1	1
s2 $\geq$ s3	0.31131908	s4 $\geq$ s2	1
s2 $\geq$ s4	0	s4 $\geq$ s3	1

Table 128, Degree of possibility of different amounts of S_k for TFNs with respect to d_2

	S1	S2	S3	S4
S1	1.0000	0.9923	0.3041	0.0000
S2	1.0000	1.0000	0.3113	0.0000
S3	1.0000	1.0000	1.0000	0.0000
S4	1.0000	1.0000	1.0000	1.0000

Table 129, The achieved amounts of S_k for criteria d_2

		W' (x_i)	w_i
Vector of weight, w' (x_i), and Vector of normalised attributes, w_i	min S1 $\geq$ S2, S3, S4	0.0000	0
	min S2 $\geq$ S1, S3, S4	0.0000	0
	min S3 $\geq$ S1, S2, S4	0.0000	0
	min S4 $\geq$ S1, S2, S3	1.0000	1

Table 130, Calculation of the weights of the alternatives with respect to criteria d_2

	Vector of weight, w' (x_i), and Vector of normalised attributes, w_i			
w' (x_i)	0.0000	0.0000	0.0000	1.0000
w_i	0.0000	0.0000	0.0000	1.0000

Table 131, Vector of the weights of the alternatives with respect to criteria d_2

10.2 Appendix II

10.2.1 *Expert Consultations*

The following is the email invitation that was sent to national and international experts within the field of carbon dioxide storage who were active in either academia or the CCS industry.

Dear X,

I hope this email finds you well.

As part of a research project on the environmental risk analysis of carbon dioxide storage underground at the Centre for Environmental Policy, Imperial College London, under the supervision of Dr. Tim Cockerill and Dr. Zen Makuch, I would be grateful if you could take 20 minutes to take part in this study. This project aims to systematically understand, quantify and present the environmental risks associated with the storage of carbon dioxide underground by studying the chain of events that could lead to major failures in storage sites using quantitative risk analysis methods as well as qualitative ones.

As part of this research project, I have asked a number of carefully selected experts within the field of carbon dioxide storage to complete a survey that I have developed, which takes 20 minutes to complete. As such, I would be grateful if you could also complete this survey. There are two parts to this survey. The full value of this research will be completed if you complete both parts of this survey. However, if you do not have the time to do so, I would be grateful if you could complete Part 1 of the survey. Each part should take approximately 10 minutes of your time. A PDF version of the completed thesis will be sent to all the experts who contribute to this study. This survey will play a central role in the completion of my PhD thesis. Please do not hesitate to ask any questions you may have by contacting me.

Email: b.orace@imperial.ac.uk

Telephone: +44(0)79 2112 2242

The survey can be taken by clicking on the link below. Furthermore, I would also be grateful if you could kindly send this email to other members within your institution who are working in areas related to carbon dioxide storage underground.

The link to the survey is:

<http://www.surveymethods.com/EndUser.aspx?B793FFE6B2FDE3EDB4>

Yours sincerely,

Behdeen Oraee-Mirzamani

Doctoral Researcher

Centre for Environmental Policy

Imperial College London

The following is the project background and a short methodological framework that was provided to the experts as part of the email invitation in order to for them to gain an overview and an understanding of the project as whole before completing the expert surveys.

Welcome to a survey assessing the risks associated with Carbon Capture and Storage

Project Background

This PhD research project aims to systematically understand, quantify and present the risks associated with the storage of carbon dioxide underground by studying the chain of events that could lead to major failures in storage sites. On the one hand, this study will enable insurance companies to understand the risks better and therefore adjust their current terms and premiums for insuring CCS projects against the risks. By doing this, insurance companies can be instructed as to which risks they have to take into account more in comparison with others so that they can minimise their financial risks by tying them down and therefore lower their premiums for insuring CCS projects. On the other hand, this project aims to assist regulators and policy makers to better understand the risks and hence legislate more effectively to address the risks associated with CCS.

Methodology

These analyses will be carried out using two different quantitative risk analysis methods. These methods are Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP). The AHP and FAHP methods have rarely been used in CCS projects individually and have not been used in combination with each other at all. However, they have been used widely in other similar industries (similar in terms of the risks involved and their potential consequences) such as Nuclear and Oil and Gas industries.

The way that this analysis is carried out is as follows. Firstly, the risk events identified in the study are going to be presented to you and other experts in the

field of carbon dioxide storage in the form of surveys. This will be done in order to find out which risks are significant and to what extent.

This survey has been designed as part of the AHP method in order to gather information from experts within the field of CCS such as yourself pertaining to the importance and criticality of the risk elements identified within a fault tree developed in this study.

After you and other experts have kindly completed the survey by comparing the risk elements within the survey pairwise and in comparison with each other, the results will then be used in order to develop the models created in this study. This will be done using the methods described above in order to obtain overall weights for the said risks and determine their relative significance to the eventual risk which is the leakage of carbon dioxide from underground storage reservoirs. As such, the overall aim of this survey is to compare the risks pairwise and then rank them in order of importance and criticality. The scale used within the ranking ranges from 1 (used when two element contribute equally to the leakage of carbon dioxide) to 9 (used when the evidence favouring one element over another is of the highest possible order of affirmation).

It is expected that the output of this survey will then partially provide the input for the AHP and FAHP methods. This will be in the form of different weights for different risk elements within the fault tree developed in the study.

This is done in order to assist the insurance industry and regulators better understand the risks associated with carbon dioxide storage underground and therefore lower insurance premiums for CCS projects and regulate more effectively and in favour of CCS projects respectively.

PART 1

1. Pair-wise comparison of the main criteria:

Please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

Please use the scale below to rank the risks from 1 to 9.

Intensity of Importance	Definition	Explanation
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
7	Very strong importance	One element is favoured very strongly over another and its dominance demonstrated in practice
5	Strong importance	Experience and judgment strongly favour one element over another
3	Moderate importance	Experience and judgment slightly favour one element over another
1	Equal importance	Two elements contribute equally to the objective.
2, 4, 6 and 8	When compromise is needed	Can be used to express intermediate values

Table 132, Saaty's 9 point scale showing fundamental importance scales in AHP

For example: If criterion **A** is favoured very strongly over criterion **B**, select **A7**. Moreover, if criterion **B** is slightly favoured over criterion **A**, select **B3**.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Percolation of CO₂ through the caprock or B: Migration of CO₂ along fracture or permeable zone	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Percolation of CO₂ through the caprock or B: Leakage of CO₂ through or along the injection well	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Percolation of CO₂ through the caprock or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Migration of CO₂ along fracture or permeable zone or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Migration of CO₂ along fracture or permeable zone or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Leakage of CO₂ through or along the injection well or B: Leakage of CO₂ through other wells	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

2. Percolation of CO₂ through the caprock:

With regards to the “*percolation of CO₂ through the caprock*”, please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

It should be noted that, the experts were asked to use the same scale for the pairwise comparisons as before

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Migration of CO₂ through the caprock or B: Diffusion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. Please give reasons for the risks you regard as most significant.

4. **Migration of CO₂ along a fracture or permeable zone:**

With regards to the *“migration of CO₂ along a fracture or permeable zone”* please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Fracturation of the caprock or B: Non-permeable fault that becomes permeable	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Fracturation of the caprock or B: Pre-existing fracture of the rock	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Non-permeable fault that becomes permeable or B: Pre-existing fracture of the rock	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

5. Please give reasons for the risks you regard as most significant.

6. Leakage of CO₂ through or along the injection well:

With regards to the *“leakage of CO₂ through or along the injection well”* please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Vertical migration through fractures in cement or B: Vertical migration at cement/casing interface	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration through fractures in cement or B: Vertical migration at cement/rock interface	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration through fractures in cement or B: Vertical migration through EDZ	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration through fractures in cement or B: Migration through cement matrix (cement wall)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration at cement/casing interface or B: Vertical migration at cement/rock interface	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Vertical migration at cement/casing interface or B:	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration at cement/casing interface or B: Migration through cement matrix (cement wall)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration at cement/rock interface or B: Vertical migration through EDZ	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration at cement/rock interface or B: Migration through cement matrix (cement wall)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Vertical migration through EDZ or B: Migration through cement matrix (cement wall)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

7. Please comment on your selections.

8. Leakage of CO₂ through other wells:

With regards to the *“leakage of CO₂ through other wells”* please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**.

Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Leakage of CO₂ through a monitoring well or B: Leakage of CO₂ through an exterior well	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

9. Please comment on your selections.

PART 2

10. Migration through the caprock (Darcy flow):

With regards to the *“Migration through the caprock (Darcy flow)”* please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Overpressure superior to capillary pressure within the caprock or B: Sufficient permeability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

11. Please comment on your selections.

12. Fracturation of the caprock:

With regards to the *“Fracturation of the caprock”* please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Overpressure of the reservoir or B: Chemical alteration by CO₂ within the caprock or along a fault	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Overpressure of the reservoir or B: Seismic event	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Overpressure of the reservoir or B: Pre-existing non-permeable fault or fracture	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Chemical alteration by CO₂ within the caprock or along a fault B: Seismic event	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Chemical alteration by CO₂ within the caprock or along a fault B: Pre-existing non-permeable fault or fracture	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Seismic event B: Pre-existing non-permeable fault or fracture	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

13. Please comment on your selections.

14. Pre-existing fracture of the caprock:

With regards to the “*pre-existing fracture of the caprock*” please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Pre-existing fault due to human exploitation (depleted oil field only) or B: Permeable fault not detected at the conception stage	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

15. Please comment on your selections.

16. Degradation of cement due to injection:

The fault tree developed as part of this study indicates that “*Vertical migration of CO₂ through the fractures in the cement*” occurs as a result of the **presence of fractures (or channels) in the cement** caused by the **degradation of cement due to CO₂ injection**.

Therefore, with regards to the “*degradation of cement due to CO₂ injection*”, please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Mechanical stresses or B: Thermal stresses	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

17. Please comment on your selections.

18. Migration of CO₂ through cement matrix (cement wall):

The fault tree developed as part of this study indicates that “*migration of CO₂ through cement matrix (cement wall)*” occurs as a result of the **presence of fractures (or channels) in the cement** caused by the **degradation of cement due to CO₂ injection**.

Therefore, with regards to the “*degradation of cement due to CO₂ injection*”, please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Initial bad quality of cement (design or setting) or B: Degradation of cement with time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

19. Please comment on your selections.

20. Degradation of cement with time:

With regards to the “*degradation of cement with time*” please compare criteria **A** with criteria **B** in each row on a scale of **1** to **9**. Select **1** when two criteria are **equally important** and have the equal probability and **9** when one criterion is **extremely more important** and probable than the other one.

	B9	B8	B7	B6	B5	B4	B3	B2	1	A2	A3	A4	A5	A6	A7	A8	A9
A: Normal aging or B: Degradation with brine (lixiviation)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Normal aging or B: Degradation by brine containing dissolved CO ₂ (and possibly other substances)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Normal aging or B: Degradation by CO ₂ supercritical (including impurities)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Degradation with brine (lixiviation) or B: Degradation by brine containing dissolved CO ₂ (and possibly other substances)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Degradation with brine (lixiviation) or B: Degradation by CO ₂ supercritical (including impurities)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
A: Degradation by brine containing dissolved CO ₂ (and possibly other substances) or B: Degradation by CO ₂ supercritical (including impurities)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

21. Please comment on your selections.

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22. Please provide some information about yourself.

Full Name

Institution/Company

Position within Institution/Company

Email Address

10.3 Appendix III

10.3.1 Experts that were contacted

Table 133 shows a list of experts that were invited to take part in the survey of this research. The table further shows the sector that each expert belonged to, their speciality and reasons behind why they were selected along with the country that their institution was located in.

Name of Organisation ¹¹	Sector (Academic / Industry)	Speciality / Justification	Country
Imperial College London – Qatar Carbonate Capture and Storage Research Centre (QCCSRC)	Academic	QCCSRC investigates key challenges in the exploitation of carbonate reservoirs by combining the expertise, local knowledge, resources and the research strengths of Shell, Qatar Petroleum, Qatar Science and Technology Park (QSTP) and Imperial College London's Energy Futures Lab respectively.	UK
Imperial College London – Department of Earth Sciences and Engineering (ESE)	Academic	Combining experimentation, imaging and modelling to study multiphase flow and reactive transport in porous media with applications to CO ₂ storage.	UK
University of Edinburgh	Academic	Analysing the natural CO ₂ reservoirs with respect to the long-term behaviour of CO ₂ in the subsurface.	UK

¹¹ The views of the experts that were contacted within the companies and academic institutions listed in table 133 do not necessarily reflect the views of their respective companies as whole.

University of Leeds Energy and Resource Research Institute	Academic	CCS for large scale power generation systems, reducing emissions from road and aviation transport, emissions from the use of renewable and future fuels (University of Leeds, n.d.).	UK
Department of Mines & Petroleum with industry partners	Industry	Working on the South West CO ₂ Geosequestration Hub in South West Australia capturing, transporting and storing CO ₂ in onshore deep saline formations.	Australia
Heriot Watt University	Academic	Analysing the risks of leakage of carbon dioxide in the north Sea and surrounding waters.	UK
Carbon Capture and Storage Association (CCSA)	Industry	CCSA brings together specialist companies in manufacturing & processing, power generation, engineering & contracting, oil & gas and minerals as well as a wide range of support services to the energy sector such as law, finance, consultancy and project management (Carbon Capture and Storage Association (CCSA), n.d.).	UK
Scottish Carbon Capture and Storage (SCCS)	Academic	SCCS is the largest carbon capture and storage research group in the UK. With internationally renowned researchers and state-of- the-art facilities (Scottish Carbon Capture & Storage (SCCS), n.d.).	UK
Error! Hyperlink	Academic	Risk assessment, focused	Australia

reference not valid.		on assessment of CO ₂ storage risks, particularly in identifying and characterising storage sites of suitable quality with adequate prospects for long-term reservoir performance and containment(Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)).	
British Geological Survey (BGS)	Industry	One of the leading institutions researching on the ways in which carbon dioxide can be stored underground.	UK
Ostfold Research Co.	Industry	Life cycle assessment of CO ₂ capture and storage	Norway
Nottingham Centre for Carbon Capture and Storage (NCCCS)	Academic	Fully integrated research centre bringing together the expertise of the British Geological Survey and the University of Nottingham. NCCCS addresses and acknowledges the need for cross disciplinary research by bringing together experts which is roughly double the size of any comparable institution in UK (Nottingham Centre for CCS (NCCCS), n.d.).	UK
CCS TLM	Industry	Practical experience of developing industrial scale integrated CCS projects having previously played leading roles in the development of projects advanced by both BP and Hydrogen Energy (CCSTLM, n.d.).	UK

CO ₂ Deep Store Ltd.	Industry	The company co-invests alongside partners and provides the development capability to enable the capture, transport or storage of CO ₂ for major industrial emitters (power stations, cement works, iron / steel / aluminium plants and similar large emitters) (CO ₂ DeepStore, n.d.).	UK
Rhead Group	Industry	Knowledge of the oil and gas sectors, and of the development of on and offshore pipeline networks including compression facilities such as those used to capture, transport and store CO ₂ underground (Rhead Group, n.d.).	UK
Massachusetts Institute of Technology's Carbon Capture and Sequestration Technologies Program (MIT CCS&ST)	Academic	MIT CCS&ST has been conducting research into technologies to capture, utilise and store CO ₂ from large stationary sources since initiated in 1989 (MIT CCS&ST, n.d.).	USA
Schlumberger Carbon Services	Industry	Experts in providing technologies and services for the long-term geological storage of carbon dioxide as a result of participating in many CCS projects worldwide backed up by a corporate history of over 80 years in the oil and gas industry (Schlumberger, n.d.).	UK
Senenergy	Industry	CO ₂ storage consultancy with expertise ranging from basin screening, site selection and	UK

		development through to storage site operation and storage monitoring, measurement and verification (Senergy, n.d.).	
UK Carbon Capture and Storage Research Centre (UKCCSRS)	Academic / Industry	UKCCSRS is a research centre that aims to provide a national focal point for CCS research and development in order to bring together the user community and academics to analyse problems, devise and carry out research and share delivery, thus maximising impact (UK Carbon Capture and Storage Research Centre (UKCCSRS), n.d.).	UK
GDF Suez	Industry	The Group has been participating with other organisations in the “France Nord” pilot CCS project on transport and storage of carbon dioxide in saline aquifers since 2010 (Carbon Capture & Storage Association (CCSA), n.d.-a).	France
University of Strathclyde	Academic	Structural and permeability architecture of faults.	UK
University of Sheffield	Academic	Develops fundamental understanding and quantitative description of CO ₂ migration in porous media at extreme conditions relevant to saline aquifers encountered in carbon sequestration (University of Sheffield, n.d.).	UK
Maersk Oil	Industry	Maersk Oil is active in innovative oil and gas extraction methods by	Denmark

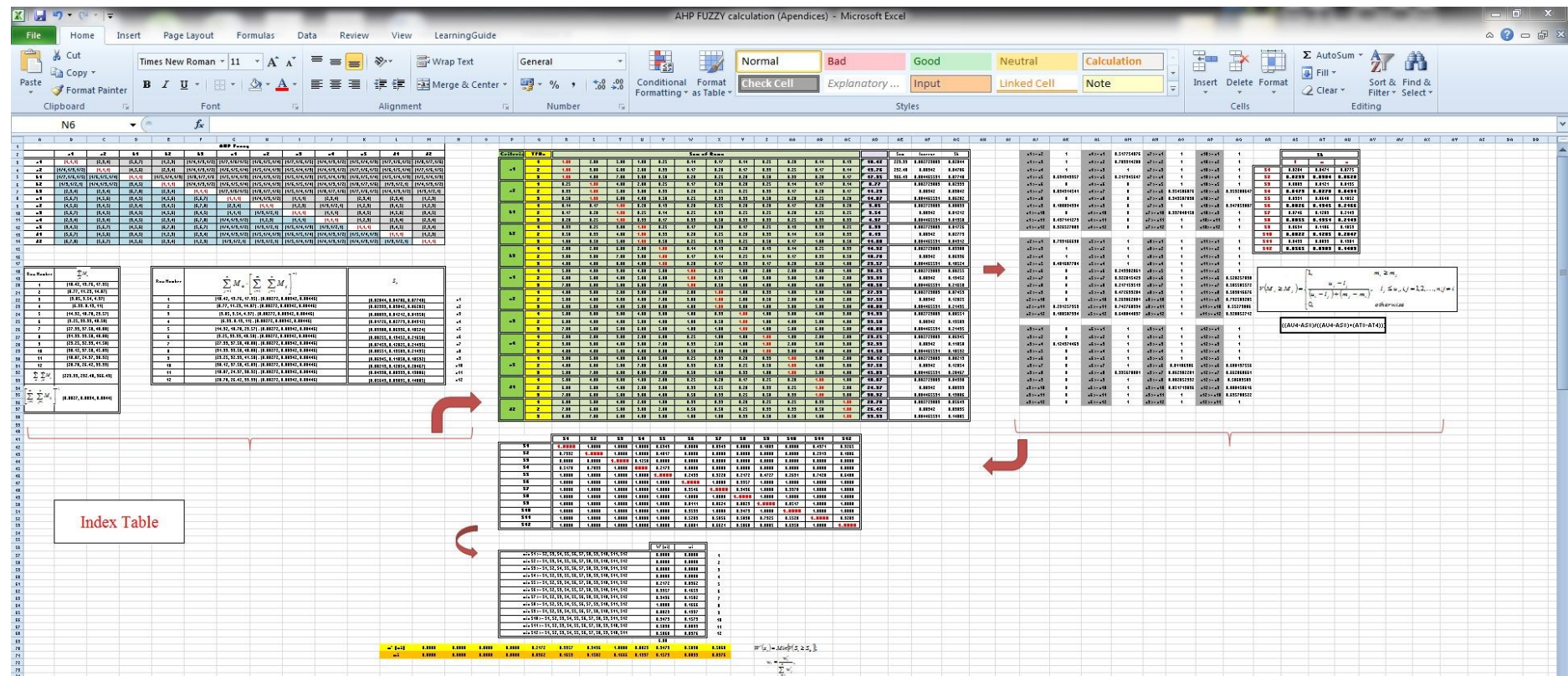
		combining EOR techniques with CCS projects (Maersk Oil, n.d.).	
Japan CCS Co., Ltd. (JCCS)	Industry	JCCS conducts investigations and studies into CCS projects in Japan as well as acting as body that brings together major companies with expertise in CCS-related fields such as electric power, petroleum and oil development (Japan CCS Co., n.d.).	Japan
British Petroleum (BP)	Industry	BP captures and stores up to one million tonnes of CO ₂ a year at its In Salah demonstration plant in Algeria.	UK
Gulf Coast Carbon Centre (GCCC)	Academic	GCCC conducts extensive studies on geological sequestration of CO ₂ in the deep subsurface, focussing on the Gulf Coast (Bureau of Economic Geology, n.d.).	USA

Table 133, List of expert participants

10.4 Appendix IV

10.4.1 Calculation steps of the Fuzzy AHP method

The way in which the FAHP technique was used in this research has been shown in this section. Furthermore, this method was modelled using Excel.



Choice Table 1

Migration from the caprock (a1)

	A	B	C	D
A1	A	(1,1)	(7,3)	(7,3)
B1	(10,17)	(1,1)	(1,1)	(1,1)
C1	(17,18,19)	(1,1)	(1,1)	(1,1)
D1	(17,18,19)	(1,1)	(1,1)	(1,1)

Choice Table 2

Diffusion (possible initiation of other mechanisms) (a1)

	A	B	C	D
A1	(1,1)	(4,5)	(7,3)	(2,3)
B1	(10,15,16)	(1,1)	(14,15,16)	(10,15,16)
C1	(18,19,18)	(2,3)	(1,1)	(1,1)
D1	(15,16,17)	(3,4)	(10,15,16)	(1,1)

Choice Table 3

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 4

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 5

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 6

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 7

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 8

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 9

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 10

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 11

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 12

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(1,1)

Choice Table 13

Fracturation of the caprock (b1)

	A	B	C	D
A1	(1,1)	(1,1)	(7,3)	(7,3)
B1	(1,1)	(1,1)	(5,7)	(5,7)
C1	(17,18,19)	(17,18,19)	(1,1)	(14,15,16)
D1	(17,18,19)	(16,17,16)	(2,3)	(

Choice Table 4				
Non-permeable rock that becomes permeable (b2)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(15,14,13)	(14,13,12)
B	(1,1,1)	(1,1,1)	(7,8,9)	(7,8,9)
C	(3,4,5)	(17,16,15)	(1,1,1)	(1,1,1)
D	(2,3,4)	(17,16,15)	(1,1,1)	(1,1,1)

Sk			
	l	m	u
S1	0.0673	0.0787	0.0988
S2	0.4709	0.5789	0.6975
S3	0.1416	0.1862	0.2485
S4	0.1139	0.1562	0.2142

TFNs		Sum of Rows				Sum	Inverse	Sk
A	1	1.00	1.00	0.20	0.25	2.45	28.67	0.0277
	2	1.00	1.00	0.25	0.33	2.58	32.82	0.03047
	3	1.00	1.00	0.33	0.50	2.83	36.10	0.034877
B	1	1.00	1.00	8.00	7.00	17.00	0.0277	0.4709
	2	1.00	1.00	9.00	8.00	19.00	0.03047	0.5789
	3	1.00	1.00	9.00	9.00	20.00	0.034877	0.6975
C	1	3.00	0.11	1.00	1.00	5.11	0.0277	0.1416
	2	4.00	0.11	1.00	1.00	6.11	0.03047	0.1862
	3	5.00	0.13	1.00	1.00	7.13	0.034877	0.2485
D	1	2.00	0.11	1.00	1.00	4.11	0.0277	0.1139
	2	3.00	0.13	1.00	1.00	5.13	0.03047	0.1562
	3	4.00	0.14	1.00	1.00	6.14	0.034877	0.2142

$$((AU4-AS8)((AU4-AS8)+(AT8-AT4)))$$

s1>=s2	0	s3>=s1	1
s1>=s3	0	s3>=s2	0
s1>=s4	0	s3>=s4	1
s2>=s1	1	s4>=s1	1
s2>=s3	1	s4>=s2	0
s2>=s4	1	s4>=s3	0.707472

	S1	S2	S3	S4
S1	1.0000	0.0000	0.0000	0.0000
S2	1.0000	1.0000	1.0000	1.0000
S3	1.0000	0.0000	1.0000	1.0000
S4	1.0000	0.0000	0.7075	1.0000

	W'(w)	wi
min S1>=S2,S3,S4	0.0000	0
min S2>=S1,S3,S4	1.0000	1
min S3>=S1,S2,S4	0.0000	0
min S4>=S1,S2,S3	0.0000	0
	1.0000	4

w'(w)	0.0000	1.0000	0.0000	0.0000
wi	0.0000	1.0000	0.0000	0.0000

$$P(M_i \geq M_j) = \begin{cases} 1, & m_i \geq m_j \\ \frac{u_i - l_j}{(u_i - l_j) + (m_j - m_i)}, & l_j \leq u_i, i,j=1,2,\dots,n, i \neq j \\ 0, & \text{otherwise} \end{cases}$$

Choice Table 5				
Pre-existing fracture of the caprock (b3)				
	A	B	C	D
A	(1,1,1)	(7,8,9)	(7,8,9)	(7,8,9)
B	(17,16,15)	(1,1,1)	(5,6,7)	(6,7,8)
C	(17,16,15)	(17,16,15)	(1,1,1)	(1,1,1)
D	(17,16,15)	(16,17,16)	(1,1,1)	(1,1,1)

Sk			
	l	m	u
S1	0.4715	0.5820	0.7070
S2	0.2483	0.3159	0.4072
S3	0.0462	0.0513	0.0592
S4	0.0458	0.0508	0.0583

s1>=s2	1	s3>=s1	0
s1>=s3	1	s3>=s2	0
s1>=s4	1	s3>=s4	1
s2>=s1	0	s4>=s1	0
s2>=s3	1	s4>=s2	0
s2>=s4	1	s4>=s3	0.9578

TFNs		Sum of Rows				Sum	Inverse	Sk
A	1	1.00	8.00	7.00	7.00	23.00	39.60	0.020501
	2	1.00	9.00	8.00	8.00	26.00	44.67	0.022386
	3	1.00	9.00	9.00	9.00	28.00	48.78	0.025252
B	1	0.11	1.00	5.00	6.00	12.11	0.020501	0.24829
	2	0.11	1.00	6.00	7.00	14.11	0.022386	0.31589
	3	0.13	1.00	7.00	8.00	16.13	0.025252	0.40718
C	1	0.11	0.14	1.00	1.00	2.25	0.020501	0.04621
	2	0.13	0.17	1.00	1.00	2.29	0.022386	0.05130
	3	0.14	0.20	1.00	1.00	2.34	0.025252	0.05916
D	1	0.11	0.13	1.00	1.00	2.24	0.020501	0.04584
	2	0.13	0.14	1.00	1.00	2.27	0.022386	0.05077
	3	0.14	0.17	1.00	1.00	2.31	0.025252	0.05832

	S1	S2	S3	S4
S1	1.0000	1.0000	1.0000	1.0000
S2	0.0000	1.0000	1.0000	1.0000
S3	0.0000	0.0000	1.0000	1.0000
S4	0.0000	0.0000	0.9578	1.0000

	W'(w)	wi
min S1>=S2,S3,S4	1.0000	1
min S2>=S1,S3,S4	0.0000	2
min S3>=S1,S2,S4	0.0000	3
min S4>=S1,S2,S3	0.0000	0
	1.0000	4

$$((AU4-AS8)((AU4-AS8)+(AT8-AT4)))$$

$$P(M_i \geq M_j) = \begin{cases} 1, & m_i \geq m_j \\ \frac{u_i - l_j}{(u_i - l_j) + (m_j - m_i)}, & l_j \leq u_i, i,j=1,2,\dots,n, i \neq j \\ 0, & \text{otherwise} \end{cases}$$

w'(w)	1.0000	0.0000	0.0000	0.0000
wi	1.0000	0.0000	0.0000	0.0000

Choice Table 9				
Vertical migration through EDZ (c4)				
	A	B	C	D
A	(1,1,1)	(1,1,1)	(1/8,1/7,1/6)	(1/7,1/6,1/5)
B	(1,1,1)	(1,1,1)	(1/7,1/8,1/9)	(1/6,1/5,1/4)
C	(6,7,8)	(7,8,9)	(1,1,1)	(1/4,1/3,1/2)
D	(5,6,7)	(4,5,6)	(2,3,4)	(1,1,1)

	Sk		
	l	m	u
S1	0.0550	0.0642	0.0769
S2	0.0552	0.0648	0.0776
S3	0.3454	0.4540	0.6008
S4	0.2909	0.4170	0.5845

	TFNs	Sum of Rows				Sum	Inverse	Sk
		1	2	3	4			
A	1	1.00	1.00	0.13	0.14	2.27	30.79	0.024239
	2	1.00	1.00	0.14	0.17	2.31	35.97	0.027799
	3	1.00	1.00	0.17	0.20	2.37	41.26	0.032473
B	1	1.00	1.00	0.11	0.17	2.28		0.024239
	2	1.00	1.00	0.13	0.20	2.33		0.027799
	3	1.00	1.00	0.14	0.25	2.39		0.032473
C	1	6.00	7.00	1.00	0.25	14.25		0.024239
	2	7.00	8.00	1.00	0.33	16.33		0.027799
	3	8.00	9.00	1.00	0.50	18.50		0.032473
D	1	5.00	4.00	2.00	1.00	12.00		0.024239
	2	6.00	5.00	3.00	1.00	15.00		0.027799
	3	7.00	6.00	4.00	1.00	18.00		0.032473

s1>=s2	0.9744056	s3>=s1	1
s1>=s3	0	s3>=s2	1
s1>=s4	0	s3>=s4	1
s2>=s1	1	s4>=s1	1
s2>=s3	0	s4>=s2	1
s2>=s4	0	s4>=s3	0.865797

$$F(M_i \geq M_j) = \begin{cases} 1, & m_i \geq m_j \\ \frac{u_i - l_j}{(u_i - l_j) + (m_j - m_i)}, & l_j \leq u_i, i, j = 1, 2, \dots, n, j \neq i \\ 0, & \text{otherwise} \end{cases}$$

$$((AU4-AS8)((AU4-AS8)+(AT8-AT4)))$$

	S1	S2	S3	S4
S1	1.0000	0.9744	0.0000	0.0000
S2	1.0000	1.0000	0.0000	0.0000
S3	1.0000	1.0000	1.0000	1.0000
S4	1.0000	1.0000	0.8658	1.0000

	W' (xi)	wi
min S1>= S2, S3, S4	0.0000	0
min S2>= S1, S3, S4	0.0000	0
min S3>= S1, S2, S4	1.0000	0.535964
min S4>= S1, S2, S3	0.8658	0.464036
	1.8658	
w' (xi)	0.0000	0.0000
wi	0.0000	0.0000
	0.0000	0.5360
		0.4640

