Development of a systemic risk management approach for CO2 capture, transport and storage projects

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“The important thing is not to stop questioning.

Curiosity has its own reason for existing.”

Albert Einstein

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Introduction: Context & Thesis Objectives

CTSC chair, financial supporter of the thesis

The current thesis has been funded by CTSC chair, which is a MINES ParisTech research program on Capture, Transport and Storage of CO_2 (CTSC). The chair covers eight main research areas including: CO_2 capture and capture energy efficiency, CO_2 Transport networks and pooled infrastructures, Risks related to CO_2 geological storage, Local and global social perception of carbon storage, Carbon economy and CTSC, Innovation and large scale diffusion of CTSC technologies, Regional scale impact assessment and Demonstration programs. Several universities, research centers, companies and local authority representatives are engaged in CTSC chair program. In MINES ParisTech, Crisis and Risk research Center (CRC), Center of Energy and Process (CEP), Center of Geoscience and CERNA (Center of Industrial Economics) are involved. Several departments of Le Havre university, Le Havre local authorities, BRGM (Bureau de Recherches Géologiques et Minières), Total, Lafarge, GDF Suez, EdF and Air Liquide are other partners of the chair [CTSC chair].

Context

Climate change has been a major concern of societies for several years. Global risks have been categorized in five groups, including economic, environmental, geopolitical, societal and technological in the latest report of World Economic Forum (WEF) [WEF, 2012]. Climate change is pointed out in two of these categories: environmental and technological, termed as "*Failure of climate change adaptation*" and "*Unintended consequences of climate change mitigation*" respectively. WEF raises a question whether our current "safeguards" are appropriate to manage emerging risks which are inherently present in our complex world; and believes that stakeholders brainstorming is essential for emerging risks management. Global risks from WEF point of view are available in Appendixes 1 and 2.

Capture, Transport and Storage of CO_2 (CTSC) is one of the technologies planned to contribute to industrial CO_2 emissions and climate change mitigation. CTSC consists of a chain of processes to collect or capture a CO_2 gas stream, transport the CO_2 to a storage location and inject it into that location. The most significant source of CO_2 emissions is the combustion of fossil fuels such as coal, oil and gas in power plants, automobiles and industrial facilities. A number of specialized industrial production processes and product uses such as mineral production (cement, lime, etc.), metal production (iron and steel, aluminum, etc.) and the use of petroleum-based products can also lead to CO_2 emissions [EPA, 2010].

CTSC is currently a constituent of global energy policy, although there are still lots of uncertainties regarding CTSC contribution and development.

CTSC is considered as a low carbon technology along with renewable energies, nuclear, increasing energy efficiency and fuel switching. The target is to halve the current CO_2 emissions by 2050 [GCCSI, 2011a]. International Energy Agency (IEA) proposes that CTSC will reduce 19% of CO_2 emissions by 2050 [IEA, 2010]. CTSC is concerned with not only climate change and energy policies, but also industry and innovation policies [GCCSI, 2011a].

While United Nations Framework Convention on Climate Change (UNFCCC) has emphasized on the importance and urgency of climate change concerns [UNFCCC, 2012], national policies seem to deal with several uncertainties. Canada's withdrawal from Kyoto protocol just after the last climate change conference in Durban (November 28-December 11, 2011) is an example of uncertain policies.

Perceptions of stakeholders on the effectiveness of CTSC are different. Although most of governments and industries intend to invest on the technology, others such as local communities and NGOs are worried about long term risks and reliability of CO_2 storage. CO_2 leakage is the most significant concern of these groups since it could lead to risks for human beings, animals and plants as well as potable water networks.

Risk Assessment and Management are essential parts of CTSC development in order to provide answers for the uncertainties and assure the control of well-understood parts of CTSC processes.

Several studies have been carried out on risk assessment of Capture, Transport and Storage technologies. Risks of CO_2 Capture and Transport are assumed to be well-understood. Therefore, classical methods have been usually applied for analyzing risks of Capture and Transport subsystems. However, CO_2 storage is known as a '*non-engineered*' part of the process, dealing with various uncertainties [Koornneef *et al.*, 2012]. Consequently, most of available risk assessment studies are focused on CO_2 storage technical aspects of risk.

What is neglected in most of available approaches is that CTSC is a complex sociotechnical system for which risks could not be analyzed individually, without taking the whole context into account. Complex system is a *system composed of many parts that interact with and adapt each other. In most cases, the behavior of such systems cannot be adequately understood by only studying their component parts. This is because the behavior of such systems arises through the interactions among those parts* [IRGC, 2010]. A sociotechnical system is a one consists of a technical part which is in interaction with a social part.

Risks associated to CTSC are not limited to technical risks. Along with technical challenges, CTSC is faced to uncertainties concerning development up to commercial scales. At the present time, seventy four large scale integrated projects are identified in the world. Only fourteen projects are in construction or operation phase [GCCSI, 2011a]. A number of projects have been cancelled or delayed for various reasons. Therefore, a major question about CTSC at the current scale of development is what are the factors explaining the success or failure of CTSC projects in different contexts?

In order to answer this question, a systemic risk management framework is proposed based on the concepts of System Dynamics and STAMP (Systems-Theoretic Accident Model and Processes), developed at Complex Systems Research Laboratory of Massachusetts Institute of Technology.

Aside from sociotechnical complexity of CTSC system, the idea comes from systemic and dynamic characteristics of risk. Systems are regularly adapting themselves to perturbations. Nevertheless, positive feedbacks lead to system destabilization by amplifying the perturbations. So, it is important to identify feedback dynamics involved in the system in order *to better anticipate when risks might emerge or be amplified* [IRGC, 2010]. In this thesis, systemic modeling is proposed as a decision making support, which provides the grounds of thinking about the components of a potentially successful CTSC project. Each stakeholder is assumed as a controller, who is responsible for maintaining safety constraints. Safety control structures are developed for several case studies to formalize the relations of stakeholders in maintaining safety constraints.

Thesis Objectives

The initial objective of the thesis was to develop an integrated risk analysis methodology. The purpose was to cover health and safety risks for the operators and local population as well as environmental risks. System dynamics was planned to be applied for modeling interactions of technical system, operators and decision makers. Following steps were anticipated for the work:

- Studying lessons learned from CTSC incidents and accidents
- Identifying the actors of CTSC chain
- Modeling the technical system and its connections with the human and organizational parts
- Dynamic analysis of risks
- Defining deviation scenarios
- Consequence analysis of scenarios
- Providing recommendations

The models were planned to be verified in a CTSC pilot plant.

The research question was progressively formulated as studying the performance of CTSC safety control system.

In the course of study, the objective and research question were modified for several reasons. The main reasons include:

1. CTSC integrated chain is an emerging technology for which few lessons learned are available. Publically available information on CTSC is restricted due to confidentiality issues. Therefore, gathering information on operational aspects of risk was a challenge.
2. Feedback loop is an essential concept of system dynamics which has to be integrated in system dynamics models. The models of technical system confirmed that feedback loops appear only when we consider interconnections of system variables and control variables. Studying such interconnections requires a great amount of data, which are not available for CTSC.
3. Discussions with experts of the domain led us to the conclusion that the most significant question in terms of integrated CTSC risk analysis is not the performance of CTSC safety control system from technical point of view. The actual concern is whether CTSC projects will be developed up to commercial scales.

Based on these facts, the research question formulation was modified in the final year of the thesis. Effectiveness of safety control structure is still in question. However, a broader definition of safety is taken into account. Safety is defined as the *absence of losses due to an undesired event* [Leveson, 1995, p.181]. Losses in this definition include *human losses, mission or goal losses, equipment or material losses and environmental losses* [Dulac, 2007, p.31]. The thesis is focused on mission or goal losses. Other kinds of failures do have impacts on mission losses.

Feedback network involved in the evolution path of the thesis objectives could be illustrated in the form of a causal graph (Figure I.1). Causal graph is a key concept of system dynamics that will be introduced in chapter 2.

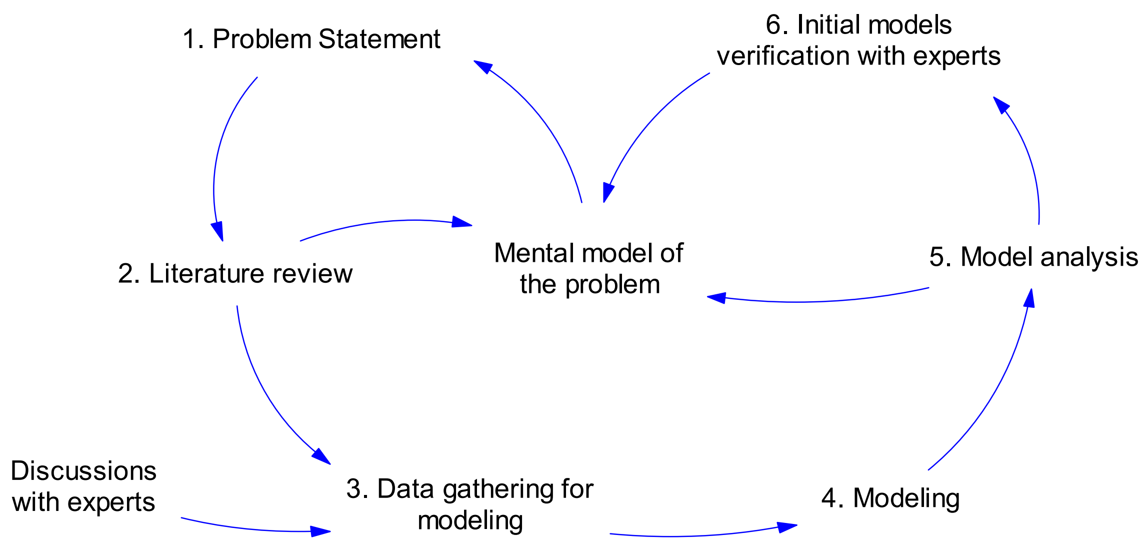


Figure I.1: Feedback network involved in the evolution path of thesis objective

Required data for modeling have been gathered from reviewing available literature and discussions with experts. Initial models have been developed, analyzed and verified with experts. Mental models of the modeler have been affected from and improved based on this process in the course of study. The problem has been consequently reformulated according to the new mental model. As illustrated in Figure I.1, mental model of the problem is at the heart of the evolution path and has been affected from literature review, model analysis and initial models verification with experts.

Manuscript outline

The manuscript contains five chapters.
CTSC contribution to climate change and an overview of CTSC projects current status are presented in chapter 1. Capture, Transport and Storage processes and associated risks are then reviewed. Different aspects of risk related to CTSC whole chain are introduced here, including Technical, HSE (Health, Safety and Environment), Policy/Strategy, Legal, Organizational/Human, Financial/Economic, Social and risks concerning the Project.
Afterwards, principal notions of risk management as well as traditional and latest risk management approaches are reviewed.
At the final section of chapter 1, available risk management methods for Capture, Transport and Storage subsystems and CTSC whole chain are presented. And we wrap up with the necessity of developing a systemic risk management framework for CTSC.
Chapter 2 deals with how system dynamics and systemic approaches could contribute to CTSC risk management. The chapter begins with the introduction of systems theory and system dynamics. After reviewing application fields of system dynamics, dynamics involved in the current CTSC context are presented. Key concepts and examples of STAMP are provided at the end of the chapter, where we explain how systemic approaches, and particularly STAMP, can be applied for studying CTSC dynamics.
Chapter 3 is devoted to the proposed methodology. The methodology steps are detailed in this chapter. Main risks involved in CTSC projects are reviewed and modeled.
Application of the methodology for some case studies is presented in chapter 4. Further discussions and comparison of case studies are provided in this chapter. The aim is to propose an improved safety control structure for CTSC projects according to the analysis of the case studies. SWOT (Strengths, Weaknesses, Opportunities and Threats) matrices are also presented to give an overall view of positive and negative aspects of the case studies.
Finally, some overall conclusions are presented in Chapter 5. Advantages and limitations of the methodology and areas for further research are also discussed in this final chapter.
Figure I.2 summarizes the manuscript outline.

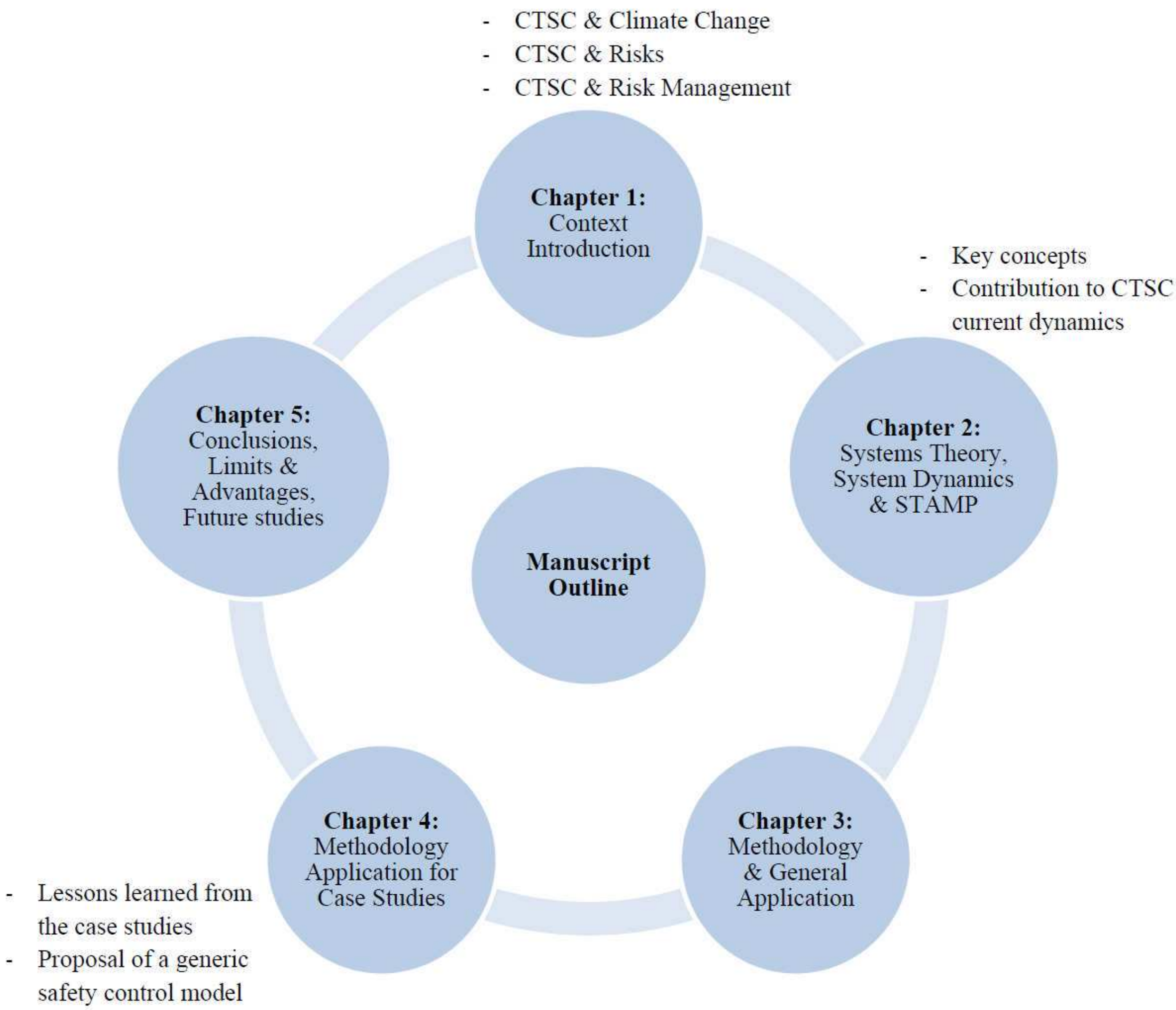


Figure I.2: Manuscript outline

Chapter 1: CTSC Technologies, Risks & Risk Management Approaches Advantages & Gaps

The purpose of chapter 1 is to introduce CTSC (Capture, Transport and Storage of CO_2), the risks associated with this innovative technology, and the gaps in available risk management approaches.

This chapter is divided into six major parts. The first three sections provide an overview of CTSC technology and its current status in the world, as well as the contribution of CTSC to climate change.

In the fourth part, a review of risks associated with CTSC subsystems and the whole chain are presented.

The fifth section focuses on the evolution of risk management approaches. Limitations of classic methods and the requirement of novel approaches for innovative technologies are discussed in this part.

In the last section of this chapter, available risk management methods for CTSC are reviewed and the necessity of developing an integrated approach is discussed.

The following two points shall be taken into consideration:

1. In this report, CO_2 storage refers to the storage in geological formations (described in section 1.3.3). Otherwise, the storage system is clearly specified.
2. In this report, CTSC is used for the integrated chain of Capture, Transport and Storage of CO_2. In a number of citations, CCS is referred to the same integrated system.

1.1 CTSC and Climate Change

Capture, Transport and Storage of CO_2 (CTSC) is one of the contribution options for mitigating industrial CO_2 emissions in the atmosphere. CTSC technology is developing along with other low carbon technologies such as renewable resources, increasing energy efficiency, fuel switching and nuclear. The set target is halving the emissions by 2050 (compared to the current amount) [GCCSI, 2011a, p.3]. The current (April 2012) amount of CO_2 in the atmosphere is equal to 394.01 ppm [ESRL, 2012].

Two main scenarios are established for CO_2 emissions reduction: Baseline and BLUE Map. The assumption in Baseline scenario is that no new energy and climate policy are introduced by governments. However, in BLUE Map scenario, the objective is to halve the emissions by 2050 (compared to 2005) by deploying existing and new low carbon technologies [IEA, 2010]. Key technologies for reducing emissions under BLUE Map scenario is illustrated in the following figure:

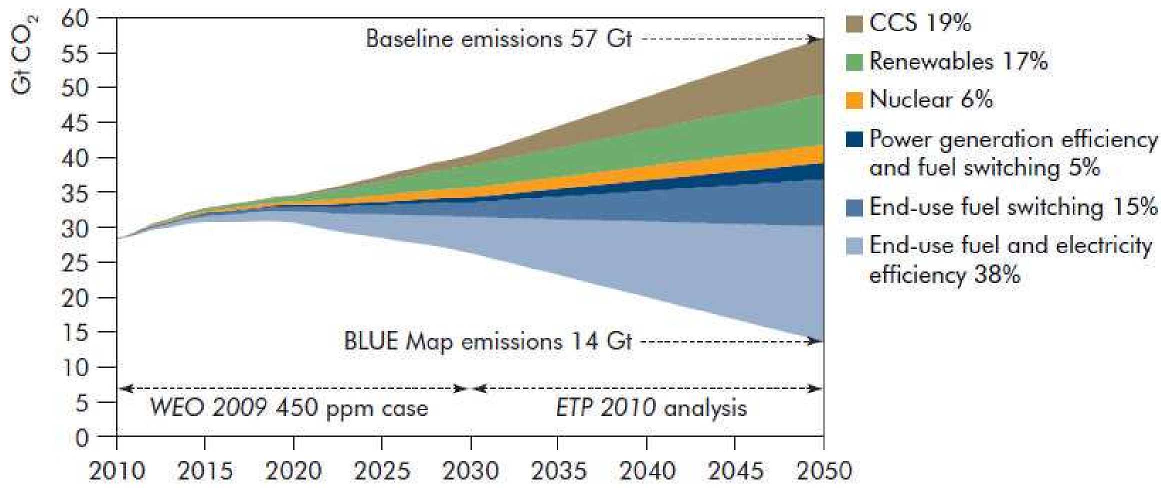


Figure 1.1: Key technologies for reducing CO_2 emissions under the BLUE Map scenario [IEA, 2010]

A European Directive has been published in 2009 to propose a regulatory framework for CTSC (geological storage of CO_2) in order to remove the legal barriers and ensure the environmentally safe development of the technology. The Directive *shall not apply to geological storage of CO_2, with a total intended storage below 100 kilotonnes, undertaken for research, development or testing of new products and processes*. According to the preliminary estimations, 7 million tonnes of CO_2 could be stored by 2020, and up to 160 million tonnes by 2030. [EU Directive, 2009]

There is not a mutual agreement about the necessity and effectiveness of CTSC in global energy policies. Non-Governmental Organizations (NGOs) are major opponents of CTSC development. An example is Greenpeace, which is an international environmental NGO. Greenpeace believes that CTSC is not ready to save the climate in time. According to the United Nations Development Program (UNDP), CTSC *will arrive on the battlefield far too late to help the world avoid dangerous climate change* [UNDP, 2007, p.145]. Energy waste, risk of CO_2 leakage, expensiveness and liability risks are some other points noticed by Greenpeace for supporting the idea of conceiving CTSC as *False Hope*. Greenpeace believes that renewable energy and improving energy efficiency are safe and cost-effective for the climate change problem. The results of a Carbon Capture Journal survey (in 2008) have been cited by Greenpeace. The survey of one thousand (1000) *climate decision makers and influencers* shows that *there is a substantial doubt in the ability of CCS to deliver. Just 34% were confident that retrofitting "clean coal technology" to existing power plants could reduce CO_2 emissions over the next 25 years without unacceptable side effects, and only 36% were confident in its ability to deliver low-carbon energy from new power stations*. Greenpeace adds that six thousand (6000) CTSC projects are required, with the injection rate of 1 million tonnes per year each, to mitigate climate change effects by 2050. [Rochon *et al.*, 2008]

CTSC refers to the chain of processes used to collect or capture a CO_2 gas stream, transport the CO_2 to a storage location and inject it into that location. An overall view of CTSC possible systems is illustrated in the following figure:

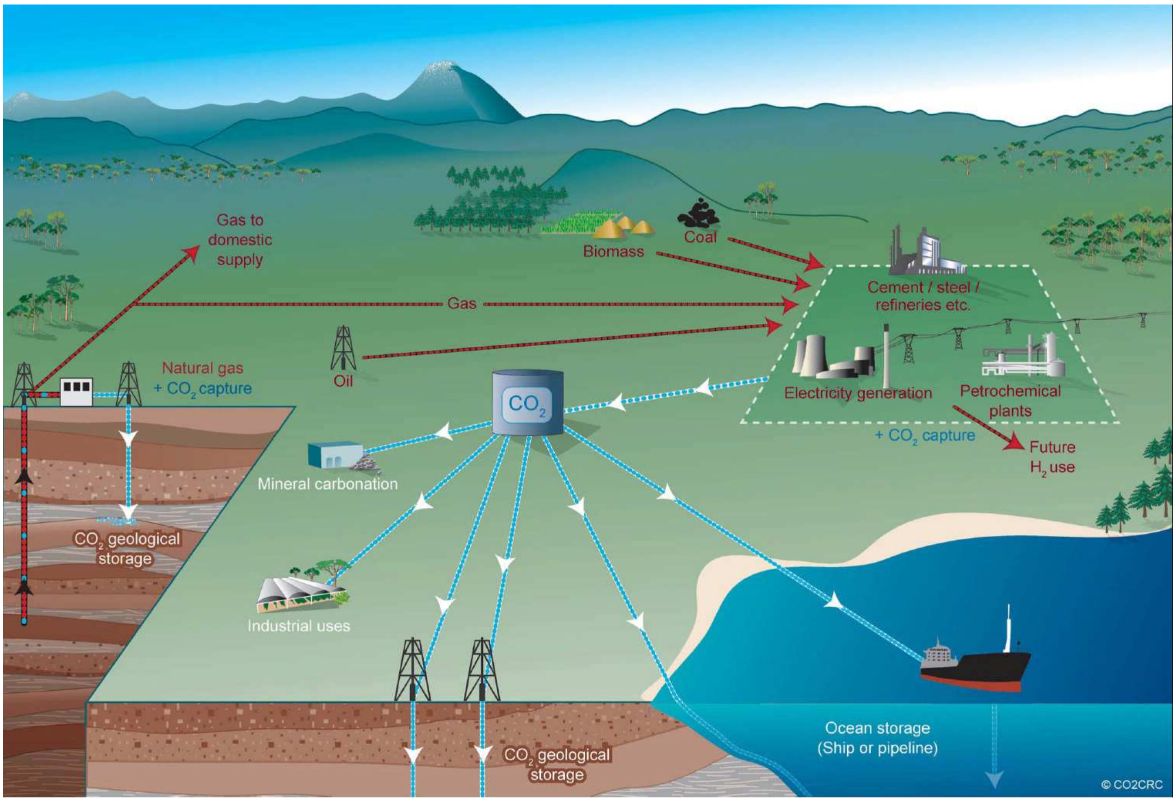


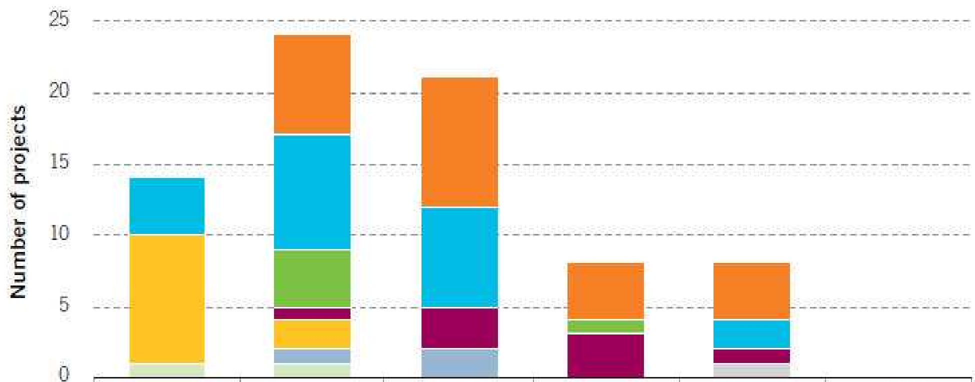
Figure 1.2: Possible CTSC systems [IPCC, 2005]

The most significant source of CO_2 emissions is the combustion of fossil fuels such as coal, oil and gas in power plants, automobiles, industrial facilities, etc. A number of specialized industrial production processes and product uses such as mineral production (cement, lime, etc.), metal production (iron and steel, aluminum, etc.) and the use of petroleum-based products can also lead to CO_2 emissions [EPA, 2010]. A summary of the most significant sources of CO_2 emissions is available in Appendix 3.

1.2 CTSC projects current status in the world

So far, seventy five Large Scale Integrated Projects (LSIP) are identified all around the world. Global CCS Institute (GCCSI) defines LSIP as the projects which involve all the three subsystems (Capture, Transport and Storage), with the storage capacity of not less than 800,000 tonnes/year for a coal-based power plant and not less than 400,000 tonnes/year for other industrial plants. [GCCSI, 2012b].

The current status of LSIP CTSC projects is summarized in the following figure:



	Identify	Evaluate	Define	Execute	Operate	**Total**
United States	0	7	9	4	4	**24**
Europe	4	8	7	0	2	**21**
Australia and New Zealand	0	4	0	1	0	**5**
Canada	0	1	3	3	1	**8**
China	9	2	0	0	0	**11**
Middle East	0	1	2	0	0	**3**
Other Asia	1	1	0	0	0	**2**
Africa	0	0	0	0	1	**1**
Total	**14**	**24**	**21**	**8**	**8**	**75**

Figure 1.3: LSIP CTSC projects by region and project phase [GCCSI, 2012b]

The activities related to the project phases, presented in Figure 1.3, are defined in Table 1.1 (a closure phase is added at the end).

Table 1.1: Definition of CTSC project phases [GCCSI, 2012b]

	Planning			*Active*		
Project Phase	**Identify**	**Evaluate**	**Define**	**Execute**	**Operate**	**Closure**
Activities: Capture & Transport	- Concept studies	- Prefeasibility studies - Estimate overall project capital cost (± 20-25%) and operating costs (± 10-15%)	- Feasibility studies - Estimate overall project capital cost (± 10-15%) and operating costs (± 5%)	- Project execution	- Asset operation	- Asset decommissioning
Activities: Storage	- Site screening studies	- Site assessment studies	- Site selection studies	- Design and installation	- Operate	- Close

Distribution of LSIPs by industry sector is shown in Figure 1.4:

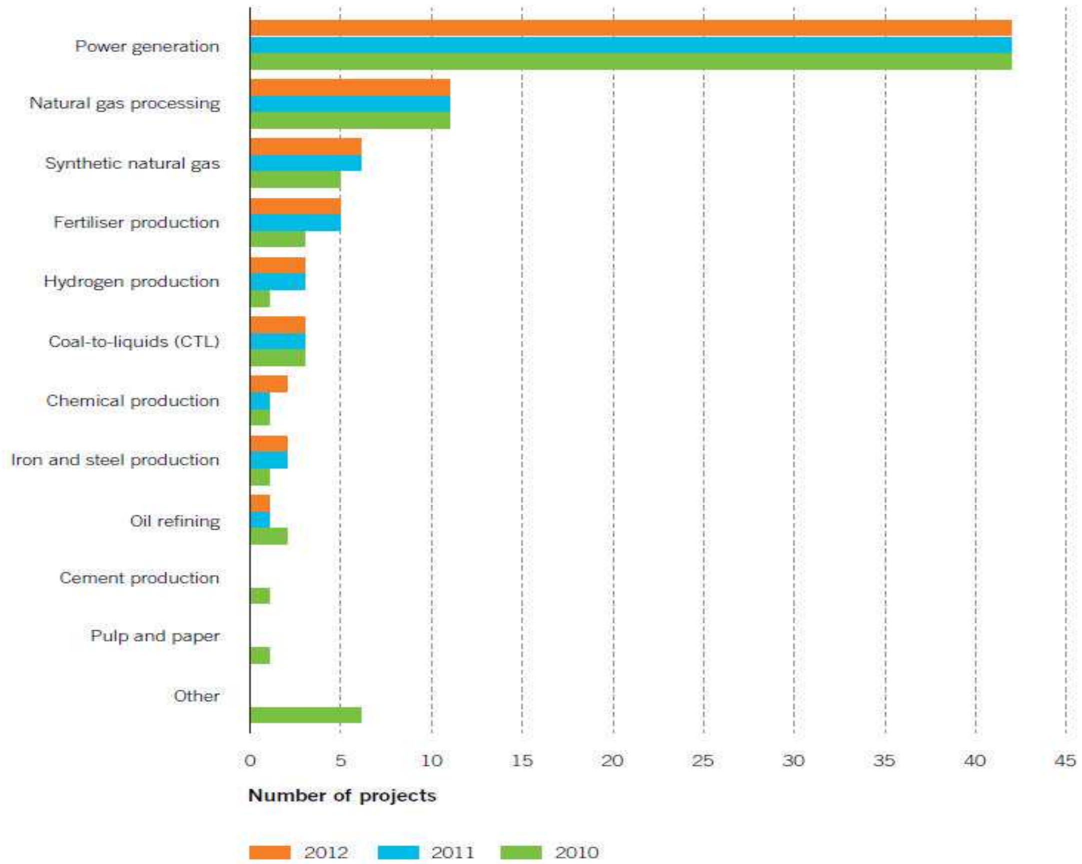


Figure 1.4: LSIPs by industry sector [GCCSI, 2012b]

Eleven CTSC projects (LSIP) have been cancelled or made on-hold between 2010 and 2011. Being uneconomic is the reason often cited for these cancellations. [GCCSI, 2011a, p.viii]

Following this brief presentation of CTSC systems current status, a general introduction of Capture, Transport and Storage technologies is provided in the next section.

1.3 CTSC Technology: An overall introduction

In this section, different processes of CO_2 Capture, Transport and Storage are presented.

1.3.1 CO_2 Capture

At present, large scale CO_2 separation units are available in natural gas treatment and ammonia production plants. However, the major purpose of such CO_2 separation is to meet the process requirements, rather than storage [IPCC, 2005, p.107]. Three main technology options are available for CO_2 capture (Figure 1.5).

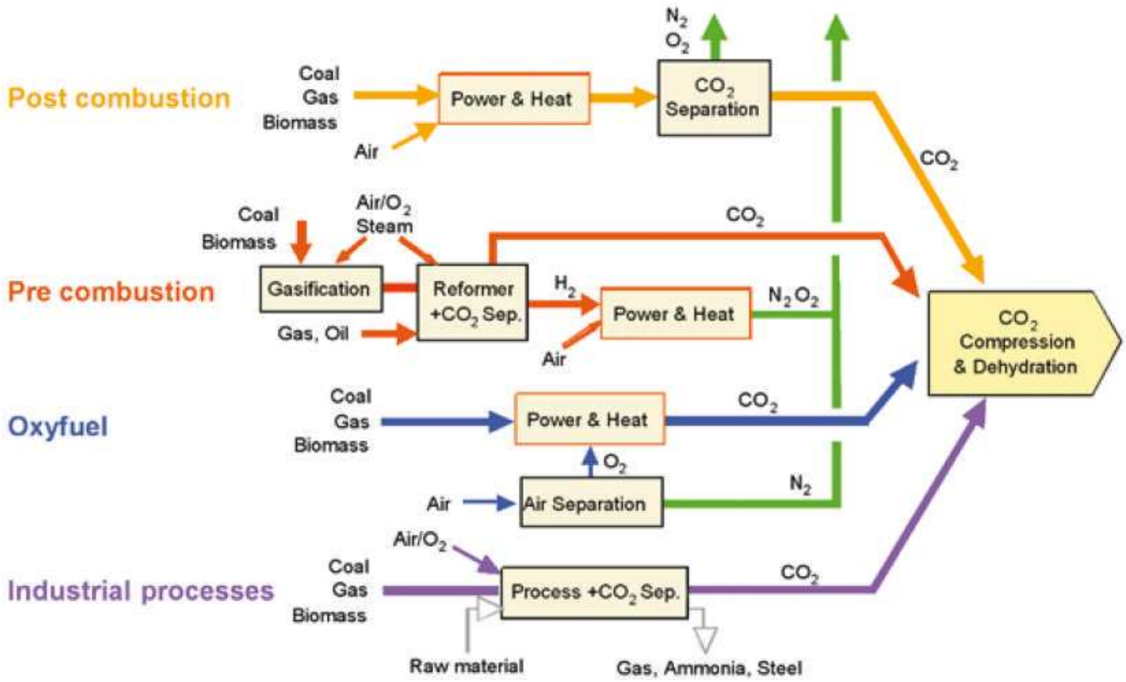


Figure 1.5: CO_2 Capture technologies [IPCC, 2005]

IPCC recognizes natural gas sweetening and steel, cement or ammonia production processes as a different category, called Industrial process capture systems.

In subsequent paragraphs, we will review the major characteristics of CO_2 Capture technologies [IPCC, 2005; Lecomte *et al.*, 2010]:

- Post-combustion: Separating CO_2 from the flue gases produced by the combustion of fossil fuels (coal, oil or natural gas) or biomass in air. Post-combustion is a significant CO_2 capture process in large scales, since the direct burning of fuel with air has been the most economic technology up to now. Nevertheless, no operational LSIP with post-combustion technology is currently available in power generation sector [GCCSI, 2011a, p.38]. Absorption with chemical solvents is currently the preferred option for post-combustion, as a result of higher efficiency and lower energy consumption and cost [IPCC, 2005, p.114]. Absorption processes will be discussed later in the current report.
- Oxy-combustion: In this system, oxygen is used for the combustion of fuel, instead of air. The result is a flue gas with high CO_2 concentrations. This technology is still under development to be deployed on commercial scale. The capture efficiency in oxy-combustion process is almost 100%. Cryogenic distillation is the most common and economic process of producing oxygen from air, for oxy-combustion technologies. [IPCC, 2005, pp.107, 122 & 127]
- Pre-combustion: consists transforming the fuel to a mixture of Carbon Monoxide and Hydrogen (Synthesis Gas), and then production of CO_2 by the reaction of Carbon Monoxide with steam in a shift reactor. The resulting mixture of hydrogen and CO_2 can then be separated into a CO_2 gas stream, and a stream of hydrogen. CO_2 could be stored, and the hydrogen is a carbon-free fuel that can be combusted to generate power and/or heat. Pre-combustion capture is more developed comparing to other capture technologies. However, it does not mean that pre-combustion technologies are more feasible in terms of commercial and economic issues. [GCCSI, 2011a, p.36]

A great amount of CO_2 is generated in the combustion process of industrial process capture systems. Therefore these systems are not the complete answer to climate change requirements [IPCC, 2005, p.111].

Two natural gas sweetening plants are currently operating. BP's In Salah plant in Algeria, and Statoil Sleipner plant in the North Sea. Almost 6.5 million tCO_2/year from natural gas sweetening is currently used in the United States EOR (Enhanced Oil

Recovery) projects. The most familiar natural gas sweetening method is using alkanolamines (such as MEA, DEA, MDEA). For high CO_2 concentrations, membrane systems are more economical [IPCC, 2005, p.112].

Details of steel, cement and ammonia production capture systems are not discussed in the present report.

Several technologies could be used to separate CO_2 in each of the above-mentioned systems (Post-combustion, Oxy-combustion, Pre-combustion). The major separation methods are as following:

- Absorption by chemical or physical solvents, or a mixture of both:

  In the case of chemical absorption, CO_2 will be absorbed from the flue gas, while contacting a chemical solvent in an absorption tower. The absorber temperature is typically between 40 and 60 °C. In the second phase of the process, CO_2 will be extracted from the rich solvent (rich in CO_2) by modification of pressure and temperature conditions. The regeneration is carried out at high temperatures (100-140 °C) and low pressure (not more than atmospheric pressure). Regenerated solvent of the second phase will be recycled to the absorption tower; while sour gas, containing CO_2, will be transported for storage or utilization. Recovered CO_2 will be typically at 0.5 bar and 99.9 vol% (figures from [IPCC, 2005, pp.115 & 116]). A typical schematic of a commercial absorption system is illustrated in Figure 1.6. The most common chemical solvents used in absorption process are aqueous solvents containing an alkanolamine (e.g. MEA, DEA, MDEA).

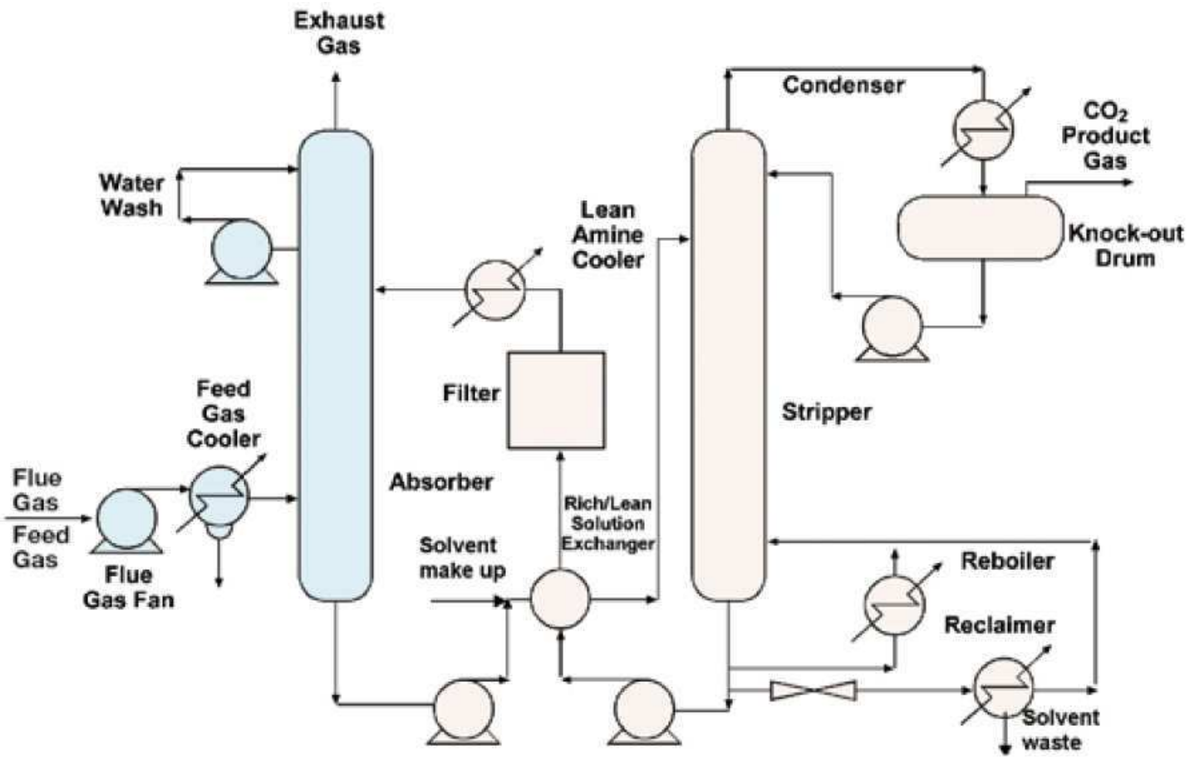


Figure 1.6: CO_2 recovery by chemical absorption, Typical Process Flow Diagram [IPCC 2005]

Efficiency and cost are the most significant concerns of such technologies, as a result of the great amount of solvent that is used for CO_2 separation. More solvent needs larger equipment and more energy for solvent regeneration. Therefore, efficiency and cost are impacted. Solvent selection is important for reducing energy consumption [IPCC, 2005, pp.109 & 117].

Degradation and corrosion products formation, and the presence of particles lead to the application of filters, carbon beds and reclaimers to maintain the solvent quality. Degradation and corrosion have been the important aspects related to absorption processes over the past few decades [IPCC, 2005, p.115]. Ammonia and heat-stable salts are the effluents generated as a result of amine decomposition [IPCC, 2005, p.118]. Sometimes, the flue gas contains NO_x and SO_x, which need to be removed before CO_2 recovery. Further research is carrying out to develop novel solvents and processes.

Regenerable solid sorbents could be also used to remove CO_2 at relatively high temperatures. Sodium and potassium oxides and carbonates are the sorbents utilized in large-scale CO_2 capture systems. Calcium oxide (CaO) is another sorbent to capture CO_2. [IPCC, 2005, p.121]

When a physical solvent is used for absorption, CO_2 is dissolved in a liquid without having a chemical reaction. Physical solvents are often organic liquids, such as methanol, pure or in aqueous phase.

A mixture of chemical and physical solvents could be also applied in order to benefit from the complementary characteristics of the solvents. Physical solvent allows cutting down the required energy for regeneration, since it could be simply regenerated by reducing the pressure, which is an economic process. [Lecomte *et al.*, 2010, pp.45-47]

- Adsorption:

  Adsorption is the process of CO_2 retention in a solid surface. Molecular sieves or activated carbon are used to adsorb CO_2. The adsorbent will be regenerated by increasing the temperature or decreasing the pressure. Efficiency of adsorption is a concern that requires the development of new materials. [IPCC, 2005, p.120].

- Separation by membrane:

  The principle of membranes is selective permeation. It means that since the gas components have different permeation rate, CO_2 as a component which permeates faster than other components will pass through the membrane. Therefore, at the end, we will have a CO_2 rich stream on the interior of membrane and a CO_2 lean stream on the exterior.

  Although membrane separation finds many current commercial applications in industry (some of a large scale, like CO_2 separation from natural gas) they have not yet been applied for the large scale and demanding conditions in terms of reliability and low-cost required for CO_2 capture systems. A large worldwide R&D effort is in progress aimed at the manufacture of more suitable membrane materials for CO_2 capture in large-scale applications. [IPCC, 2005, p.110]

- Cryogenic process:

  In this process, CO_2 can be separated from the gas by reducing the temperature and modification of CO_2 to a liquid or solid phase.

Separation systems described in the previous paragraphs are shown in Figure 1.7.

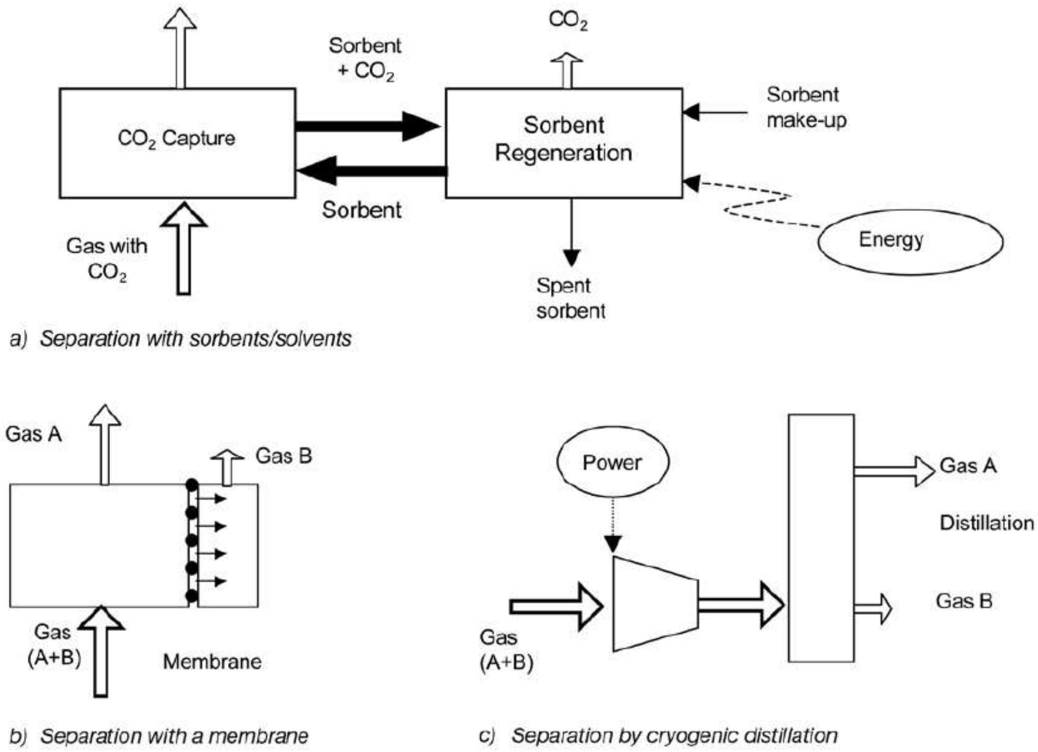


Figure 1.7: General schemes of CO_2 Capture main separation processes [IPCC, 2005]

After capturing, CO_2 will be transported to the storage location. Available CO_2 transportation modes are summarized in the next section.

1.3.2 CO_2 Transport

CO_2 can be transported to the storage location either by onshore/offshore pipelines, by tankers or ships. CO_2 transport is not a new technology, particularly in North America. According to GCCSI (2011a), almost 6000 km of CO_2 pipelines are currently in service. *This network transports approximately 50 Mtpa of CO_2 and has been developed over the past 40 years*. The majority of this transport network is in the United States, where CO_2 is mostly transported from natural resources to oilfields as part of CO_2 Enhanced Oil Recovery (EOR). Long distance CO_2 pipelines are not available in Europe, except Turkey. Recently, some networks have started to operate in the North Sea and the Netherlands [Gale & Davison, 2004; Serpa *et al.*, 2011]. CO_2 transportation in the US is in the industrial scale. Some industries believe that the difference between the US and Europe is due to the more populated areas, more complicated process of obtaining permits, and social acceptance issues in Europe [Jallais, 2011].

CO_2 is in supercritical state while transporting with a pressure of more than 74 bar (being in supercritical state means that CO_2 is at a temperature and pressure above its critical point). Critical temperature and pressure of CO_2 are 31.1°C and 73.9 bar respectively (Figure 1.8). When CO_2 is in supercritical state, it will have the viscosity of a gas, but the density of a liquid. CO_2 transportation by pipeline on the liquid state (10 bar and -40°C) is still in the research phase. For long distances, CO_2 will be transported by ship in liquid phase (20 bar and -20°C) [Lecomte *et al.*, 2010]. Road and rail tankers are the other technically feasible options. These systems transport CO_2 at -20°C and 20 bar. However, they are uneconomical compared to pipelines and ships, except on a very small scale, and are unlikely to be relevant to large-scale CTSC [IPCC, 2005].

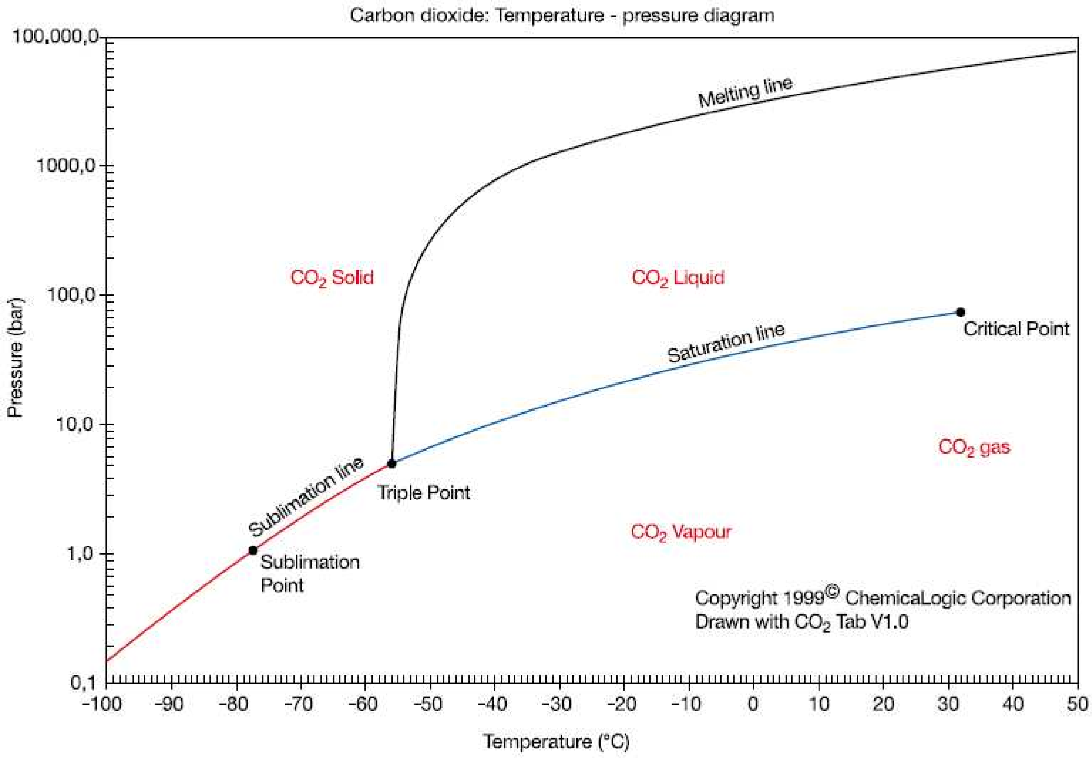


Figure 1.8: CO_2 phase diagram [IPCC, 2005]

It has been estimated that to support the 3400 industrial scale CCS projects by 2050 in the IEA BLUE map scenario, over 200,000 km of pipeline would need to be constructed, at a cost of US$2.5 to 3 trillion. The estimation of CO_2 Europipe consortium for Europe is 22,000 km by 2050 [GCCSI, 2011a, pp.47-49].

The succeeding phase of CTSC process could be either the storage of CO_2 or utilization of CO_2 in the industries. This concept will be discussed in the following section.

1.3.3 CO_2 Storage and utilization

Several methods are available to store or use the captured and transported CO_2. Principal methods of CO_2 storage are as follows [IPCC, 2005]:

- Geological storage:

  CO_2 can be stored in various geological formations. The most significant options are illustrated in Figure 1.9:

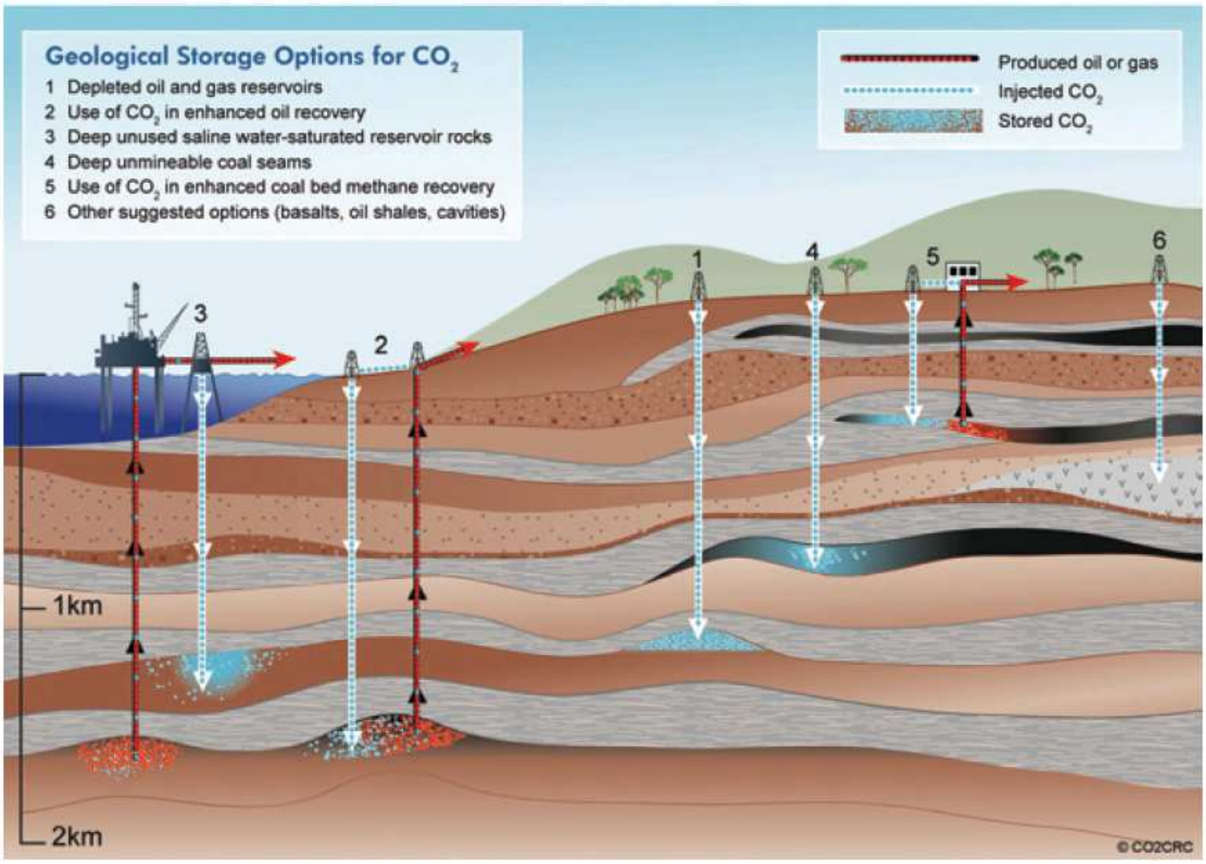


Figure 1.9: CO_2 geological storage options [GCCSI, 2011a]

  As noted before, transported CO_2 to the storage location is in supercritical phase. When CO_2 is injected in a geological formation, its density will increase with depth until about 800m or more. Therefore, the injected CO_2 is in a dense supercritical state.

- Ocean storage:

  In this case, CO_2 will be compressed, transported by a ship and directly injected into the ocean (in liquid phase) at a depth greater than 1000 meter, where CO_2 would be mostly isolated from the atmosphere for centuries. Ocean storage will have critical effects on the ocean ecosystem and there are still legal restrictions on the development of this option.

- Mineral Carbonation or Mineral Sequestration:

  Mineral carbonation is based on the reaction of CO_2 with calcium or magnesium oxide to form insoluble carbonates. Magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$) are the products of such reactions. The carbonates are stable for a long time and can be used for *construction, mine reclamation or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks*. Mineral carbonation is classified as a CO_2 reuse technology by particular references [GCCSI, 2011b, p.127].

As mentioned at the beginning of the chapter, ocean storage and mineral carbonation are not in the scope of the current research. The risks of these technologies are completely different from the geological storage risks.

CO_2 reuse is another alternative for reducing CO_2 emissions. CO_2 reuse is defined as *any practical application of captured CO_2 that adds value (such as revenue generation, or environmental benefit), and which can partially offset the cost of CO_2 capture* [GCCSI, 2011b]. Enhanced Oil Recovery (EOR), production of chemicals such as urea, beverage carbonation, food processing, preservation and packaging, pharmaceutical processes, horticulture, pulp and paper processing, refrigeration systems, welding systems, fire extinguishers, and water treatment processes are some examples of the existing CO_2 uses. Enhanced Coal Bed Methane recovery (ECBM), polymer processing, mineralization and production of liquid fuels (like methanol) are the emerging CO_2 utilization processes. [GCCSI, 2011b; IPCC, 2005]

EOR is a well-known reuse option for CO_2, particularly in the United States. According to GCCSI, *EOR will remain the dominant form of CO_2 reuse in the short and medium term due to its maturity and large-scale utilization of CO_2*. GCCSI believes that EOR plays a significant role in the development of large-scale CTSC projects. [GCCSI, 2011b]

An estimation of CO_2 storage capacity has been published in IPCC report (Table 1.2).

Table 1.2: Storage capacity of different reservoirs [IPCC, 2005]

Reservoir type	Lower estimate of storage capacity ($GtCO_2$) [a]	Upper estimate of storage capacity ($GtCO_2$) [a]
Oil and gas fields	675 [b]	900 [b]
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

[a] The storage capacity includes storage options that are not economical.
[b] These numbers would increase by 25% if undiscovered oil and gas fields were included in this assessment.

The Europe capacity range is between 30 and 577 $GtCO_2$ [Thibeau & Mucha, 2011]. The degree of uncertainty is unavailable for the estimated figures of CO_2 storage capacity. However, the European commission confirms that there is sufficient storage capacity to 2030. [De Coninck *et al.*, 2009]

1.4 CTSC technology and risks

In order to understand why a systemic risk management framework is required for CTSC chain, CO_2 properties and potential risks are first presented in this part. Afterwards, the risks of CTSC activities are reviewed.

1.4.1 Health and safety aspects of exposure to CO_2

Carbon dioxide is a colorless, odorless, harmless, non-flammable gas (at normal temperature and pressure, i.e. 20°C and 1 atm.). CO_2 is a constituent of the atmosphere and a necessary ingredient in the life cycle of animals, plants and human beings. In addition, there are large amounts of CO_2 in the ocean, about 50 times of atmospheric amount of CO_2 [Johnsen *et al.*, 2009; Serpa *et al.*, 2011]. *The classification system of Transport Dangerous Goods, International Maritime Organization/International Maritime Dangerous Goods and International Civil Aviation Organization/International Air Transport Association, all classify carbon dioxide in class 2.2, non-flammable, noncorrosive and non-poisonous gases. Carbon dioxide and its products of degradation are not legally classified as toxic substance; it is non-hazardous on inhalation, non-irritant and does not sensitize or permeate the skin.*

However, chronic effects on humans follow from long-term exposure to airborne carbon dioxide concentrations of between 0.5 and 1% resulting in metabolic acidosis and increased calcium deposits in soft tissues. The substance is toxic to the cardiovascular system and upper respiratory tract at concentrations above 3%.

- *As an asphyxiate carbon dioxide presents the greatest danger. If atmospheric oxygen is displaced such that oxygen concentration is 15-16%, signs of asphyxia will be noted.*
- *Protective equipment and clothing required in the processing industries include full face-piece respirators to prevent eye contact and appropriate personal protective clothing to protect the skin from becoming frozen by the liquid.* [IPCC, 2005, p.145]

As CO_2 is 1.5 times denser than air (CO_2 MW=44)*, there will be a tendency for any CO_2 leaking from pipework or storage to collect in hollows and other low-lying confined spaces which could create hazardous situations. The hazardous nature of the release of CO_2 is enhanced because the gas is colorless, tasteless and is generally considered odorless unless present in high concentrations* [IPCC, 2005, p.390]. According to the standards, a concentration of 0.5% is acceptable for a continuous exposure to CO_2, while it will be dangerous if the concentration is more than 5%. Occupational exposure limits for CO_2 are summarized in Table 1.3:

Table 1.3: Occupational exposure standards for CO_2 [IPCC, 2005]

	Time-weighted average (8 hour/day, 40 hour/week)	Short-term exposure limit (15 minutes)	Immediately dangerous to life and health
OSHA permissible exposure limit [a]	5000 ppm (0.5%)		
NIOSH recommended exposure limit [b]	5000 ppm (0.5%)	30,000 ppm (3%)	50,000 (5%) [d]
ACGIH threshold limit value [c]	5000 ppm (0.5%)		

[a] OSHA: US Occupational Safety and Health Administration (1986)

[b] NIOSH: US National Institute of Occupational Safety and Health (1997)

[c] ACGIH: American Conference of Governmental Industrial Hygienists

[d] Corrected based on http://www.cdc.gov/niosh/idlh/124389.html, accessed June 19, 2012

A more comprehensive list of exposure limits is available in Appendix 4.

According to DNV, incidents related to CO_2 could be categorized in three main groups [Johnsen *et al.*, 2009]:

- Fire extinguisher systems: As summarized by US Environmental Protection Agency (EPA), *from 1975 to 2000, a total of 51 carbon dioxide incident records were located that reported a total of 72 deaths and 145 injuries resulting from accidents involving the discharge of carbon dioxide from fire extinguishing systems. Prior to 1975, a total of 11 incident records were located that reported a total of 47 deaths and 7 injuries involving carbon dioxide. Twenty of the 47 deaths occurred in England prior to 1963; however, the cause of these deaths is unknown*. (The oldest reference of these figures dates back to 1910 [EPA, 2000])
- Pipelines: According to the US Office of Pipeline Safety, statistics on pipeline incidents could be summarized as follows: *In the period of 1986-2001, 11 incidents related to pipeline transport of CO_2 are reported with one fatality and two injuries. According to the statistic log, the fatality was associated with welding work and not as a direct consequence of pipeline operation. Nine of the incidents were related to the pipeline (all onshore), whereas the remaining two were located at the pumping station. In the period of 2002- 2008, 18 incidents related to pipeline transport of CO_2 are reported with no fatalities and injuries. Nine of these incidents were solely related to the onshore pipeline itself, whereas the remaining were related to incidents at pump/meter station, terminal/tank farm piping and equipment, including sumps*.
- Natural outgassing of CO_2: Two examples are mentioned in this category of incidents. Lake Nyos, Cameroon in 1986, with 1700 fatalities within 20 km of the lake; and Lake Monoun, Cameroon in 1984, killing 37 local residents.

The reader is referred to the DNV report [Johnsen *et al.*, 2009] for more information on the above-noted incidents. A list of CO_2 vessel ruptures until today is also available in the same report.

1.4.2 CTSC: risks associated to each phase & to CTSC chain

De Coninck *et al.* believe that the risks of CTSC are difficult to identify, not only technically but due to the stakeholders different perceptions of risks. Perceptions of energy policy and requirement of low-carbon energy could also affect the perceptions of CO_2 storage risks. [De Coninck *et al.*, 2009]

In this section, we firstly summarize the risks related to each phase. Afterwards, the risks of CTSC whole system are discussed.

1.4.2.1 Risks associated to CO_2 Capture

The most fundamental risks in CO_2 capture processes are associated with the vent gas produced from the capture plant, as well as liquid and solid wastes. The captured CO_2 stream may contain impurities which would have practical impacts on CO_2 transport and storage systems and also potential health, safety and environmental impacts. SO_2, NO, H_2S, H_2, CO, CH_4, N_2, Ar and O_2 are the impurities that will be available in the CO_2 stream, depending on the capture process type. Moisture of CO_2 from most capture processes has to be removed to avoid corrosion and hydrate formation during transportation [IPCC, 2005, p.141]. Problems of impurities will be readdressed in the next parts (1.4.2.2 & 1.4.2.3).

The energy required to operate CO_2 capture systems reduces the overall efficiency of power generation or other processes, leading to increased fuel requirements, solid wastes and environmental impacts relative to the same type of base plant without capture [IPCC, 2005, p.107].

Another major concern about CO_2 capture is the cost of capture technologies [GCCSI, 2011a, p.34]. Several research and development studies are carrying out to find the cost reduction methods.

IPCC believes that *monitoring, risk and legal aspects associated with CO_2 capture systems appear to present no new challenges, as they are all elements of long-standing health, safety and environmental control practice in industry.* [IPCC, 2005, p.107]

CO_2 capture and compression processes are listed as gas processing facilities in several governmental, industrial and finance guidelines. Typical engineering design, commissioning and start-up activities associated with petrochemical facilities are applicable to CO_2 capture and compression. For example HAZard OPerability (HAZOP) studies are conducted on a routine basis for new facilities [IPCC, 2005, p.146].

1.4.2.2 Risks associated to CO_2 Transport

Risks related to CO_2 transportation obviously depend on the transportation mode and on the local topography, meteorological conditions, population density and other local conditions. However, carbon dioxide leaking from pipelines or other modes of transportation could result in potential hazards for human beings and ecosystem. Therefore, public acceptance is a critical issue in large scale development of CO_2 pipelines [IPCC, 2005].

Leakage is defined as the main safety issue for CO_2 pipelines in some research studies. *Significant quantities of other components in the CO_2 may affect the potential impacts of a pipeline leak or rupture*. De Visser *et al.* specified the following Short Term Exposure Limits (STEL) and maximum recommended level of impurities in the CO_2 stream. (STEL: Maximum allowed exposure limit for a period of 15 minutes without adverse health effects). Typical CO_2 volume concentration transported by pipeline is over 95%. For the figures of Table 1.4, the authors set a concentration of 100% for CO_2 as the reference to define the levels of H_2S and CO [De Visser *et al.*, 2008].

Table 1.4: Maximum and recommended level of impurities in CO_2 from a health and safety point of view [De Visser *et al.*, 2008]

Component	STEL (ppm)	Maximum level (not corrected) (ppm)	Safety factor	Recommended maximum level (ppm)
CO_2	10,000	1,000,000	-	-
H_2S	10	1000	5	200
CO	100	10,000	5	2,000

Corrosion is another major problem associated to CO_2 pipelines. To minimize the corrosion, impurities such as hydrogen sulphide or water have to be removed from the CO_2 transported stream. Selecting corrosion-resistant materials for pipelines is also important to avoid corrosion. Corrosion rate, risk of hydrate formation and risk of water freezing will increase in the presence of free water. The amount of free water should be maintained below 50 ppm [Serpa *et al.*, 2011]. Other experts propose different limits for water concentration. The limit for De Visser *et al.* is 500 ppm. Corrosion rates are in the order of mm/year in case of free water presence and in the order of µm/year when CO_2 is dry. [De Visser *et al.*, 2008; Seiersten, 2001]

Impurities could also change the thermodynamic behavior of the stream. As a result, velocity and pressure drop in the pipeline are subject to change; and transport cost will change accordingly [Serpa *et al.*, 2011]. Two phase flow could lead to the damage of compressors and other equipment, and hence should be avoided.

Existing gas pipelines are widely used for CO_2 transportation. The main problems of the existing pipelines are the adequacy of design pressure and remaining service life. CO_2 pipelines normally operate in 85-150 bar, while natural gas pipelines operation pressure is below 85 bar. A great number of existing pipelines have been in service for 20-40 years [Serpa *et al.*, 2011].

1.4.2.3 Risks associated to CO_2 Storage

According to [BRGM, 2005], there are two types of risks concerning geological storage of CO_2, "local risks" and "global risks". As the examples of local risks, the authors point out the risks for human beings, animals and plants above ground, contamination of potable water, interference with deep subsurface ecosystems, ground heave, induced seismicity, and damage to mineral or hydrocarbon resources.

IPCC has categorized the local risks almost the same as BRGM in three groups [IPCC, 2005, p.242]:

- *Direct effects of elevated gas-phase CO_2 concentrations in the shallow subsurface and near-surface environment*
- *Effects of dissolved CO_2 on groundwater chemistry*
- *Effects that arise from the displacement of fluids by the injected CO_2*

GCCSI argues that CO_2 storage will not have an impact on surface water resources, since the groundwater production occurs in depths of zero to 300 m, while CO_2 will be stored at more than 800 m. [GCCSI, 2011a, p.59]

"Global risks" refer to the release of CO_2 in the atmosphere, which brings the initial objective of CO_2 storage (reducing atmospheric CO_2 emissions) into question.

Impurities such as H_2S, SO_2 and NO_2 could increase the risks. For instance blow-outs containing H_2S are more toxic than blow-outs containing CO_2. The acid generated from the dissolution of SO_2 in groundwater is stronger than carbonic acid formed by dissolution of CO_2. [IPCC, 2005, p.250]

Wright presents the following schematic for illustrating that risks during the lifecycle of a CO_2 storage project are at the highest level near the later stages of injection [Wright, 2011]. The profile is similar to the one presented by [Benson, 2007]. Risk reduction over time occurs due to the *pressure dissipation* and *residual trapping of CO_2 in the pore spaces* [GCCSI, 2011a, p.60].

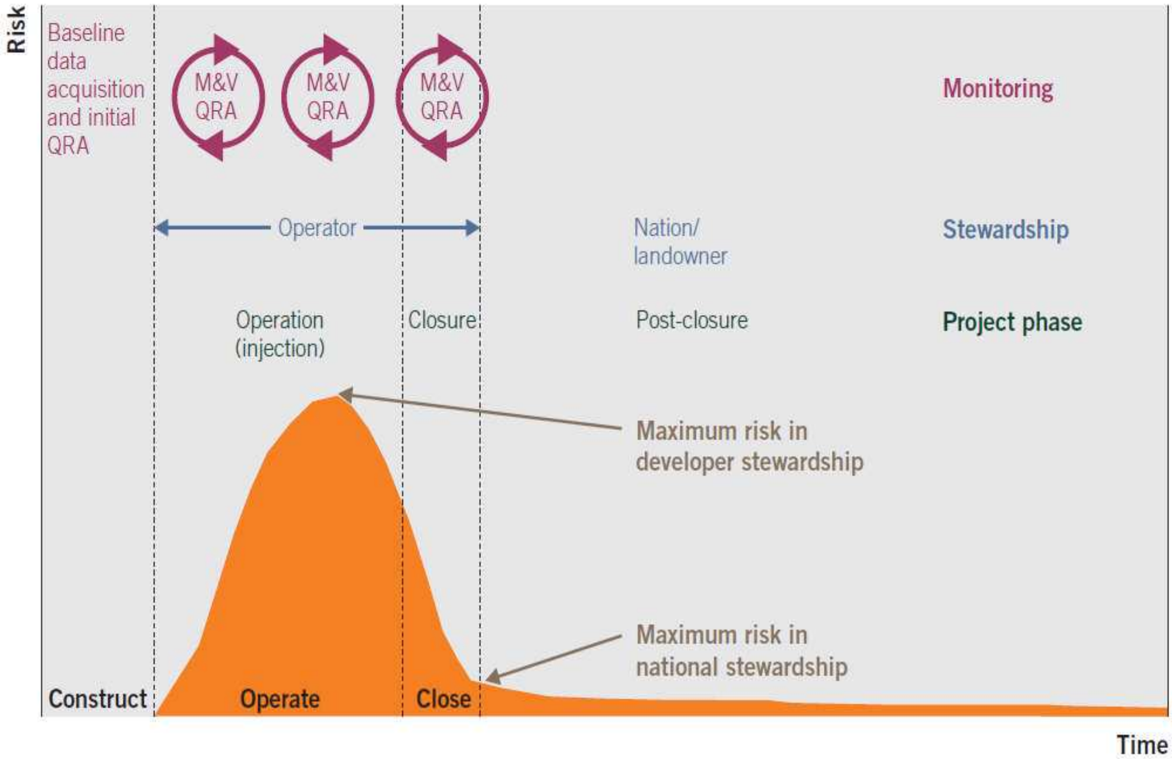


Figure 1.10: Schematic risk profile for a storage project [GCCSI, 2011a]

Source: Wright (2011), based on InSalah project
Note: M&V = Monitoring and Verification, QRA = Quantitative Risk Assessment

1.4.2.4 Risks associated to CTSC whole chain

In addition to risks related to each subsystem of CTSC chain, it is essential to analyze the risks associated to CTSC whole system. Eight major groups of risk are identified:

1. Technical risks:

   Technical issues have been developed in the previous sections (sections 1.4.2.1-3)
2. Risks related to CTSC project:

Mainly include the risks that affect the project progress, particularly the risks related to the project schedule, cost and performance; and development to commercial scales.

3. Social (Public acceptance) risks:

   Public acceptance is a risk that could significantly affect CTSC projects development. An example is Barendrecht project, in the Netherlands, which was cancelled due to public disagreement [CCJ, 2010]. De Coninck *et al.* believe that *the companies are not worried that CO_2 capture and storage will fail for technical reasons. One of the concerns, however, is potential public resistance to CCS, and some companies indicate that governments should step in to provide neutral information to the lay public* and i*t is imperative to find a common language for the characterization and communication of risk both among professionals and between professionals and the public* [De Coninck *et al.*, 2009].

4. Policy/Strategy risks:

   Policy uncertainties are defined as a major risk to CTSC projects development. GCCSI defines four policy landscapes that affect CTSC technology (Figure 1.11) [GCCSI, 2011a, pp.ix & 70]. CTSC is an innovative technology which is involved in global and local climate change and energy strategies. Therefore, the following policy issues could be concerned with CTSC.

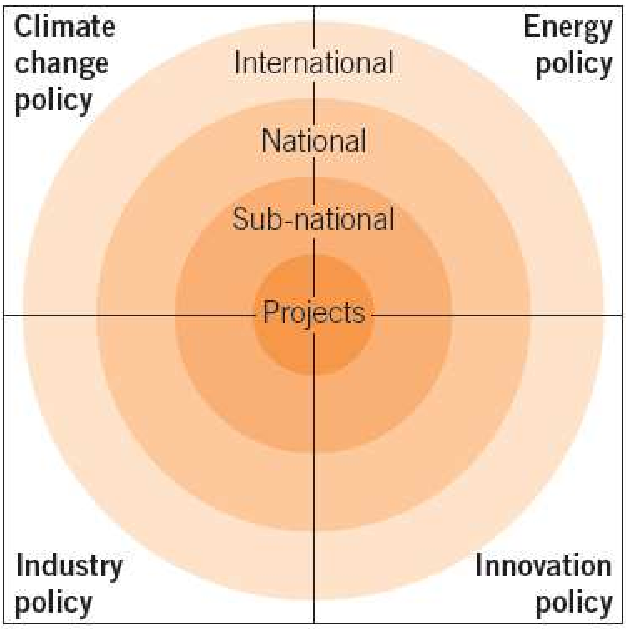


Figure 1.11: Scope of policy landscapes related to CTSC [GCCSI, 2011a]

Policies are not the same in different countries, and are strictly dependent of the policies regarding Climate Change. Canada's withdrawal from Kyoto protocol after the last climate change conference in Durban, held at the end of 2011, is an example of changing policies.

Nevertheless, the policy making of CTSC is a complex issue, depending on several points. United Kingdom submitted seven projects to the European Commission within the framework of NER300 program (European Union funding program for financing demonstration projects of CTSC and renewable energy technologies) [NER300, 2010]. In May 2011, 65 renewable and 13 CTSC projects were submitted for NER300. The energy policy of Japan has been changed since the March 2011 earthquake and tsunami. The new energy plan is more relied on fossil fuels, and accordingly, CTSC could be included in the new program of Japan [GCCSI, 2011a].

5. Health, Safety and Environmental (HSE) risks:

   Technical matters, notably impurities, leakage and corrosion may lead to HSE problems. A number of HSE concerns have been already discussed in section 1.4.1.

6. Regulatory or legal risks:

   According to a survey committed by GCCSI, regulatory issues are a significant challenge for CTSC projects [GCCSI, 2011a, p.88]. Several international and regional regulations could cover the requirements of CTSC technology. These regulations need to be transposed into national or domestic laws. De Coninck *et al.* argue that IPPC Directive (96/61/EC, as amended) is applicable for CO_2 Capture in Europe. The IPPC Directive is the European Commission Directive on industrial emissions. The authors point out that *liquefied CO_2 is already transported in significant quantities by road, ship and pipeline across the EU and is regulated in accordance with dangerous goods laws and regulations*. However, Environmental Impact Assessment Directive (85/337/EEC, as amended) of European Commission could be applied for pipelines and pumping stations. As mentioned by De Coninck *et al.*, EU Directive on CTSC *does not sufficiently deal with all legal uncertainties concerning the capture and transport of CO_2 derived from CCS facilities*. In spite of the availability of EU Directive for CTSC, *under current European law, it is uncertain whether CO_2 that is captured and then stored would be classified as* "*waste*". If so, the European waste laws could be applicable for CO_2 storage. This concern is currently the subject of several research studies. [De Coninck *et al.*, 2009]

7. Organizational and human risks:

   CTSC is a complex sociotechnical system which includes not only three technical components of Capture, Transport and Storage, but also an organizational structure containing a group of actors. The organizational and human risks are derived from such a complexity. The complex and sociotechnical systems will be defined in section 1.6.2.

8. Financial/Economic risks:

   As previously noted, some projects have been cancelled due to financial issues. However, GCCSI believes that governments financial support have not changed in 2011. Approximately US$ 23.5 billion has been funded for CTSC all around the world [GCCSI, 2011a]

Considering such an overview of risks associated to CTSC activities, a list of thirty nine risks is made based on several references, among others the documents of different projects such as Longannet, Lacq, Barendrecht, and the recent reports of GCCSI [GCCSI, 2009a; GCCSI, 2011a; Longannet, 2011; Feenstra *et al.*, 2010; Kerlero de Rosbo, 2009; CCP, 2007; Lacq Project, 2012].

Afterwards, the project phase(s) related to each risk is specified. Six main phases are distinguished, which are not necessarily similar to GCCSI phases (presented in Table 1.1).

1. Opportunity:

   The beginning period, when negotiations are carried out on the feasibility of CTSC project

2. Definition and planning:

   The phase when responsibilities and authorities of stakeholders are defined, and a planning is made for the project

3. Engineering:

   Design and sizing of installations are performed in this phase.

4. Construction:

   This phase deals with construction and installation of required infrastructure and equipment.

5. Operation (Injection of CO_2):

   The period during which CO_2 is injected into the geological formation

6. Post-injection (Monitoring) (also called "post-closure"):

   means *the period after the closure of a storage site, including the period after the transfer of responsibility to the competent authority.* [EU Directive, 2009].

At the next step, the nature of each risk and the nature of consequences are identified. Tables of risks and their nature will be presented in Chapter 3.

The risks are inevitably interconnected and could not be studied independently.

To analyze the reasons why a CTSC project might not be progressed, the risks related to the very first phases of the project are extracted from the overall list. The result is a list of eighteen major risks (Table 1.5).

Table 1.5: Major risks affecting the very first phases of the project

Major risks affecting CTSC project progress (in the first phases)			
1	Project permits not obtained	10	Unavailability of a monetary mechanism for CO_2
2	Technology scale-up	11	Geographical infrastructure
3	Public Opposition	12	Lack of financial resources
4	Lack of knowledge/qualified resources for operating the unit	13	Lack of political support
5	Legal uncertainties	14	High cost of project
6	Uncertainties in stakeholders requirements/perceptions - Communication problems	15	Unavailability of regulations regarding different types of storage (offshore/onshore)
7	Public availability of sensitive information	16	Uncertainties regarding the storage performance (capacity/injectivity/containment)
8	Change in policies/priorities	17	Model and data issues
9	Financial crisis impact on financial support of CCS projects	18	Uncertainties related to storage monitoring

In Chapter 3, we will readdress these major risks and review the risks that could be analyzed with our systemic approach, explained subsequently.

1.5 Risk Management: concepts and evolution of approaches

Definitions of risk and risk management will be firstly introduced in this section. The second part provides a review of classic and modern risk management approaches.

1.5.1 Definition of main concepts

Risk is often defined as a combination of two parameters: the probability and the severity of hazards.

From project management point of view, risk is “*uncertain event or condition that, if it occurs, has a positive or negative effect on a project’s objectives.*” [PMBOK, 2008]

The most comprehensive definition of risk in system safety engineering is the one specified by Nancy Leveson [Leveson, 1995, p.179]. In her definition, risk is a combination of four components: hazard severity, hazard likelihood, hazard exposure and likelihood of hazard leading to an accident, as illustrated in Figure 1.12.

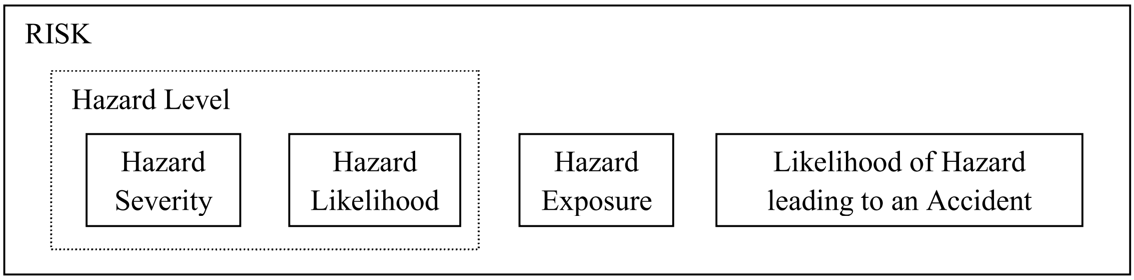


Figure 1.12: Components of Risk [Leveson, 1995]

Risk Management is defined in several references [Sadgrove, 2005; Magne & Vasseur, 2006; Desroches *et al.*, 2006; Desroches *et al.*, 2007; Garlick, 2007; Koivisto *et al.*, 2009; Mazouni, 2008]. What will be referred in the present report as “Risk Management” is illustrated in Figure 1.13.

Risk Management includes three main steps of analysis, evaluation and treatment of risk. In the risk analysis process, the scope is defined and the risks are identified and estimated. Afterwards, the risks are evaluated. The combination of risk evaluation and risk analysis is called risk assessment. Treatment is the final stage of risk management, where proposals for action are made and finally risks are reduced and controlled. The control process leads us to identify new risks or review the previously defined ones, and go back to the risk analysis phase. This loop is shown in Figure 1.13.

Risk acceptance and risk communication are specified as the last phases of risk management procedure by some authors [Condor *et al.*, 2011].

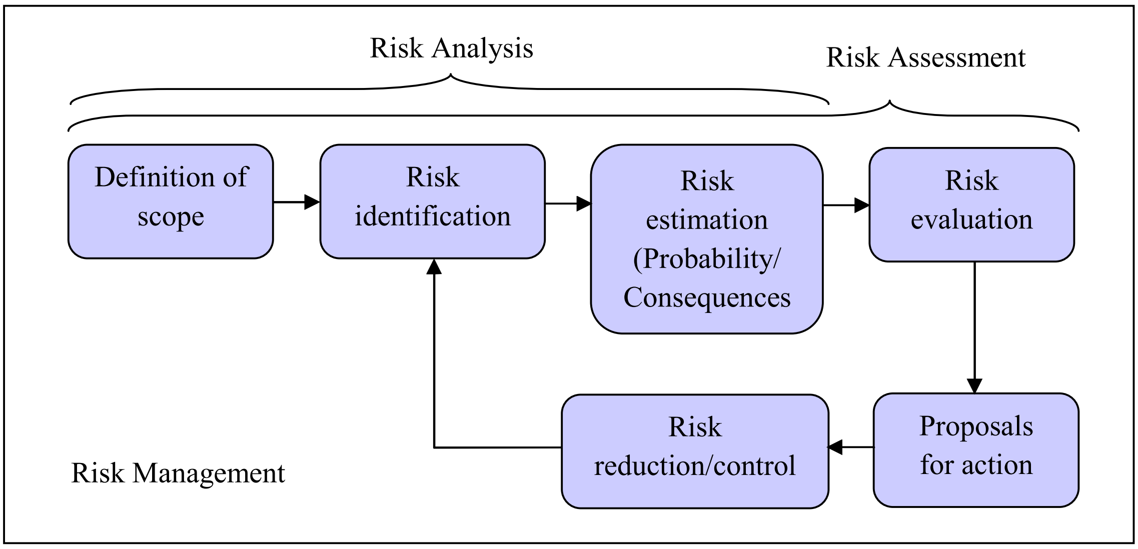


Figure 1.13: Risk Analysis, Risk Assessment and Risk Management process (adapted from [Koivisto *et al.*, 2009])
(based on IEC 60300-3-9: 1995, AS/NZS 4360: 2004, and ISO/IEC 73: 2002)

1.5.2 Classic and modern risk analysis, assessment and management methods

Tixier *et al.* have already reviewed 62 risk analysis methodologies of industrial plants. The authors have categorized risk analysis methods in four main groups: deterministic, probabilistic, qualitative and quantitative. They conclude that a combination of several methods is necessary for making risk analysis more efficient.

Deterministic methods take into consideration the products, the equipment and the quantification of consequences for various targets such as people, environment and equipment. Probabilistic methods are based on the probability or frequency of hazardous situation apparitions or on the occurrence of potential accident. As they noted: *The great majority of methods are deterministic, because historically operators and public organizations have initially tried to quantify damages and consequences of potential accidents, before to understand why and how they could occur.* [Tixier *et al.*, 2002]

Quantitative Risk Assessment (QRA) methods aim to put figures on the likelihood and consequences of risk. A number of experts do not believe that quantitative approach is the best adapted way for modern complex sociotechnical systems. Some of them argue that semi-quantitative methods are less complicated and less time consuming [Dulac, 2007; Kerlero de Rosbo, 2009; Altenbach, 1995]. Dulac mentions Failure Modes and Effect Analysis (FMEA), Failure Modes and Effect Criticality Analysis (FMECA), actuarial approaches and Probabilistic Risk Assessment (PRA) as the most common QRA methods.

According to Dulac, t*o manage risk in complex engineering systems, it is necessary to understand how accidents happen* [Dulac, 2007]. Therefore, the notion of accident and accident models will be introduced in this part.

Accident is an *unplanned and undesired loss event* which results in human, equipment, financial or information losses [Leveson, 2009]. Hollnagel defines "accident model" as *a stereotypical way of thinking about how an accident occurs* [Hollnagel, 2004, p.44]. Leveson (1995) believes that accident models can be used even for accident investigations or accident prediction.

Accident models have been evolved over time. Leveson has categorized the accident models in four main groups [Leveson, 1995, pp.186-204]:

- Basic Energy Models
- Domino and Single Event Models
- Chain-of-Events Models
- Systemic Models

Definition of each category is provided in the following paragraphs.

- **Basic Energy Models:** are the oldest types of models, in which accidents are the *result of an uncontrolled and undesired release of energy* (Figure 1.14).

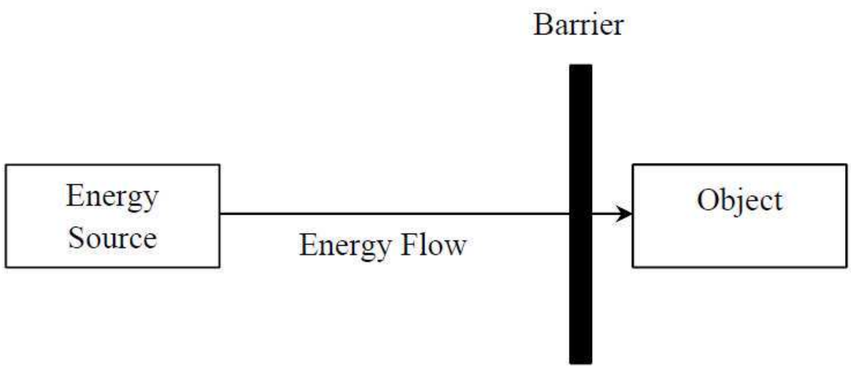


Figure 1.14: Basic energy model of accident [Leveson, 1995]

Accidents can be prevented here by controlling the Energy Flow path between the energy source and the object (Figure 1.14).

Basic energy models have been then extended in order to be applicable to a wider group of accidents. However, the scope of all energy models *is limited to energy processes and flows*. Therefore, *more sophisticated models of causal factors* are needed. Leveson classifies these models in three subsequent categories, although she affirms that *many categorizations are possible* [Leveson, 1995, p.188].

- **Domino and Single Event Models:** Leveson believes that *unsafe conditions* are the earliest focus in industrial safety. *Unsafe human acts* come next in industrial accidents explication. Different examples are pointed out for Domino and Single Event Models, including Domino Models, The (US) National Safety Council Model and Epidemiological Models.

Domino model of accidents was proposed by Heinrich (1931). According to the domino theory, we can prevent an accident by removing one or more blocks located before the accident block (Figure 1.15).

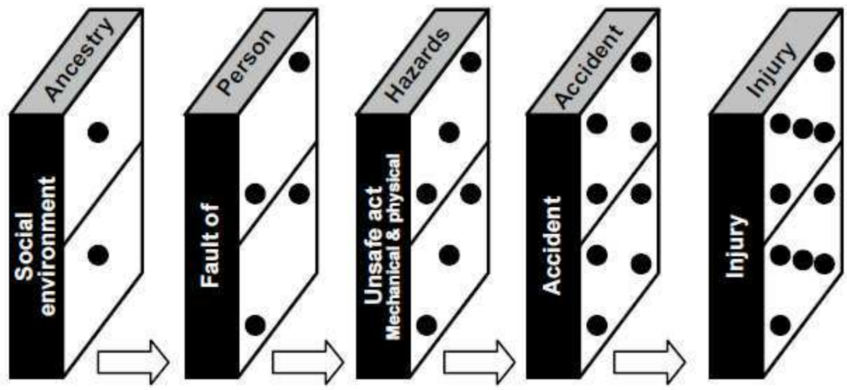


Figure 1.15: The domino theory [Hollnagel, 2004]

(original reference: [Heinrich, 1931])

Epidemiological models were firstly presented by John Gordon in the 1940s. He describes accident as spreading a disease, including three elements: *agent (physical energy)*, *environment* and *host (victim)*. In this theory *accidents are the result of complex and random interactions between these three things and cannot be explained by consideration of only one of the three* [Leveson, 1995, p.192].

Epidemiological accident models are defined as a separate independent group by Hollnagel (2004).

- **Chain-of-Events Models:** Leveson distinguishes this third category from the previous ones by noting that multiple events are included in this group. An example of such models is Johnson's MORT (Management Oversight and Risk Tree) model, developed in 1980 for US Nuclear Regulatory Commission. MORT is a logic diagram, including And / Or gates, used for accident investigation.

- **Systemic accident models:** Systemic accident models consider the accident as an emergent or normal phenomenon. In systemic models, accident occurs as a result of complex interactions of system elements. Systemic models highlight the dynamic and nonlinear aspects of systems. Leveson argues that new approaches are required in accident models and safety engineering. Such necessity arises due to several reasons, and among them *fast pace of technological change*, *changing nature of accidents*, and *increasing complexity of systems* [Leveson, 1995; Leveson, 2004a].

Dulac describes that traditional risk analysis methods, such as Failure Modes and Effect Analysis (FMEA), Fault Tree Analysis (FTA) and Probabilistic Risk Assessment (PRA), are based on event chain accident approach. Therefore, the traditional methods of risk analysis are inappropriate for modern complex systems, because the interactions between different components of the system are not considered in these methods. The author also argues that organizational approaches *have made an important contribution to system safety by emphasizing the organizational aspects of accidents*. Even so, the organizational approaches often oversimplify the engineering part of the system [Dulac, 2007]. Hollnagel confirms the idea of Dulac, and proposes to find alternative methods of risk assessment for complex systems. [Hollnagel, 2004]

Based on this reasoning, Leveson has developed a new accident model, called STAMP (Systems-Theoretic Accident Model and Processes). This new accident model is based on systems theory concepts. In this sociotechnical model, she takes into account several actors of the system, from legislatures to company top management, project management, operations management and lower levels. She argues that lack of constraints imposed on the system design and on operations is the main cause of an accident, instead of a series of events. According to Leveson, STAMP model could be applied to any accidents in complex systems [Leveson, 2004a]. The details of STAMP model approach will be presented in Chapter 2.

The notion of “systemic risk” has been also developed in several references, and among others [IRGC, 2010]. IRGC (International Risk Governance Council) uses the OECD (Organisation for Economic Co-operation and Development) definition and defines systemic risks as the *risks affecting the systems on which society depends. Systemic risks are characterized by complexity, uncertainty and ambiguity*. [IRGC, 2010; OECD, 2003]

Hellström affirms that risks of innovative technologies are systemic, as they are connected to the social, economic and political infrastructure. The author argues that an integrated assessment of risk and innovation is indispensable. He believes that emerging technological innovation is systemic in the sense that it could not be separated from other aspects of the society. The author suggests the integration of governance concepts in risk management, to make a systemic risk management approach [Hellström, 2003]. In his recent paper, Hellström presents the recommendations of the OECD project on emerging risk (2000-2002). A main recommendation is to *focus on perceptions, experience and communication among actors* in order to manage these issues as a dynamic source of risk. OECD argues that new risk management approaches are required for emerging technologies. The new approaches must involve all the stakeholders, including public. The public needs to be involved even in identification of risks. The author mentions that the new methodologies for analyzing emerging technological risk should be systemic [Hellström, 2009].

In addition to integrity, the concept of “dynamic risk analysis” has been also remarked in the innovative risk analysis approaches. Garbolino *et al*. believe that *due to the complexity of the industrial systems and their own dynamic in time and space, the risk assessment methods need to be supported by a systemic vision of their processes*. As they affirm in their article, modeling the industrial systems is indispensable to better understand their behavior in normal and abnormal modes [Garbolino *et al*., 2009].

1.6 Risk Management and CTSC

1.6.1 Available Risk Management approaches for CTSC: status and limitations

So far, several works have been carried out on risk management of CTSC all around the world. In subsequent paragraphs, we will mention some examples of these methods to finally make out the necessity of developing a systemic framework for CTSC risk management.

Most of the available risk assessment or management methods are focused on one subsystem (Capture, Transport or Storage). Due to the uncertainties concerning the reliability of CO_2 storage, risk analysis studies particularly concentrate on the storage. A great number of studies only analyze the technical risks, and believe that the risks of Capture and Transport could be studied by classic methods.

1.6.1.1 CO_2 Capture: available Risk Management approaches

According to International Risk Governance Council (IRGC), risks associated to CO_2 capture technologies (except the innovative ones) are similar to a great number of industrial processes for which codes, standards and operating procedures have been developed. Consequently, risks related to CO_2 capture are currently well understood. [IRGC, 2009]

In France, analysis of major risks for CO_2 Capture is carried out based on ICPE [Bertrane, 2011]. ICPE (Installation Classée pour la Protection de l□Environnement) is the regulatory framework applicable to CO_2 Capture in France. ICPE is a French legislation for classified installations, transcribed from Seveso II. □Classified installation□is defined as *any industrial or agricultural operation likely to create risks or cause pollution or nuisance, notably in terms of local residents□health and safety* [ICPE website 1].

Seveso II is a European Directive on the control of major-accident hazards involving dangerous substances. The Directive *is aimed at the prevention of major accidents which involve dangerous substances, and the limitation of their consequences for man and the environment, with a view to ensuring high levels of protection throughout the Community in a consistent and effective manner*. [Eurlex website]

Energy institute has recently published a guidance on hazard analysis of onshore CO_2 capture and pipeline structures. The major risk highlighted in this report is the risk of CO_2 leakage or energy release throughout the system, which may lead to equipment, human or economic losses. PHAST software is used to carry out the dispersion calculations. PHAST is a hazard analysis package developed by DNV. The authors affirm that it is essential to keep the risk ALARP (As Low As Reasonably Practicable).

The remaining risk has to be acceptable for workers, the whole public and internal/external regulatory authorities. [Energy Institute, 2010]

1.6.1.2 CO_2 Transport: available Risk Management approaches

Neele *et al.* recommend that Quantitative Risk Assessment (QRA) methods, *as used for instance in the natural gas transportation industry*, could be used to study the HSE risks of CO_2 pipelines. In the report of CO_2Europipe project, the authors propose a standard risk management method for European pipeline infrastructure. DNV practice [DNV, 2010] and ISO 31000 on Risk Management [ISO 31000, 2010] are recommended to be used. *The aim of the CO_2Europipe project is to study the requirements for the development of a large-scale CO_2 transport infrastructure in Europe, between 2020 and 2050* [Neele *et al.*, 2011].

The base of risk analysis for CO_2 transport in France is GESIP n°2008/01 (Safety Study guide, published by Groupe d'Etudes de Sécurité des Industries Pétroliers et chimiques) [Bertrane, 2011].

Koornneef *et al.* from Utrecht University have reviewed the uncertainties regarding quantitative risk assessment of CO_2 transport by pipelines. They have studied the significant parameters in release and dispersion of CO_2 from pipelines and the effects on human beings health. The assessed sources of uncertainties are: failure rates, pipeline pressure and temperature, section length, diameter, orifice size, type and direction of release, meteorological conditions, jet diameter, vapor mass fraction in the release and the dose‐effect relationship for CO_2. Two failure scenarios are considered: puncture and full bore rupture. Based on the results of their study, rupture is more significant than puncture. Therefore m*itigation of risks should be focused on reducing the probability and consequences of large releases and less on reducing the probability and consequences of small scale leaks*. [Koornneef *et al.*, 2010]

1.6.1.3 CO_2 Storage: available Risk Management approaches

EU Directive presents the risk assessment process of CO_2 storage in four steps: Hazard characterization, Exposure assessment, Effects assessment and Risk characterization. Definition of each step is summarized in the following paragraphs [EU Directive, 2009]:

1) Hazard characterization: means *characterizing the potential for leakage from the storage complex*. This includes specifying the potential leakage pathways, potential leakage rates, process specifications affecting potential leakage (e.g. maximum reservoir pressure, maximum injection rate and temperature)
2) Exposure assessment: is carried out *based on the characteristics of the environment and the distribution and activities of the human population above the storage complex, and the potential behavior and fate of leaking CO_2 from potential pathways*.
3) Effects assessment: includes the effects on *particular species, communities or habitats linked to potential leakage*, as well as the biosphere (*including soils, marine sediments and benthic waters*). The effect of CO_2 stream impurities and new substances generated through CO_2 storage shall be also studied.
4) Risk characterization: covers the safety and integrity aspects of the storage site in the short and long term. This step is performed based on the three previous steps of risk assessment, explained above.

Condor *et al.* have recently reviewed ten available risk assessment methodologies for CO_2 storage. These methods are summarized in Table 1.6. The methods could be categorized in probabilistic/deterministic and qualitative/quantitative as previously noted from Tixier *et al.* (2002). The authors argue that quantitative methods are not appropriate for CO_2 storage at the current level of development, due to lack of required data. They believe that risks may be higher at the beginning of a CTSC project [Condor *et al.*, 2011].

Table 1.6: Available Risk Assessment methodologies for CO_2 storage [Condor *et al.*, 2011]

Risk Assessment method	Description	Goal
FEP	Features, Events and Processes	Scenario development
VEF	Vulnerability Evaluation Framework	Framework for regulators and technical experts
SWIFT	Structured What-If Technique	Hypothesis elaboration
MCA/MAUT	Multi-Criteria Assessment / Multi-Attribute Utility Theory	Evaluation of alternatives in multiple objectives
RISQUE	Risk Identification and Strategy using Quantitative Evaluation	Hazard and consequence mapping
CFA/SRF	Certification Framework Approach / Screening and Ranking Framework	Risk estimation based on probabilities of occurrence in individual features
MOSAR	Method Organized for a Systematic Analysis of Risk	Risk Identification and Prevention
ESL	Evidence Support Logic	Identification of uncertainties in decisions
P&R	Performance and Risk	Risk mapping in wellbores under the criteria of degradation scenarios
SMA	System Modeling Approach	Risk estimation based on probabilities

In France, BRGM is one of the predominant institutes working on risk management of CO_2 storage. BRGM specialists study the probable impacts of CO_2 leakage on drinkable water aquifers, human health and environment. [Fabriol, 2009; Bouc *et al.*, 2009]

FEP (Features, Events, Processes) analysis is one of the approaches which has been already applied for risk assessment of CO_2 storage. FEP is a method for defining scenarios relevant to safety assessment of the geological disposal of radioactive wastes. The same approach has been implemented for long-term geological storage of CO_2. In the field of CO_2 storage, "Feature" refers to the geological formation and its characteristics. "Events" are what may or will happen in the future, for example earthquake. And "Processes" are the ongoing matters that influence the evolution of the system, like the erosion of the land surface. As a result of workshop discussions and brainstorming, a database has been developed for CO_2 storage including 200 FEPs in eight categories. (for details, refer to Quintessa report [Savage *et al.*, 2004])

FEP analysis has been applied for different CO_2 storage projects, such as Weyburn [PTRC, 2004] or Illinois Basin-Decateur project [Hnottavange-Telleen *et al.*, 2009].

Oldenburg *et al.* have developed a certification framework to certify the effectiveness and safety of CO_2 storage. They have reviewed some available risk assessment methods for storage, including a system-modeling approach (CO_2 PENS), which studies the whole CTSC chain, from capture to storage. However, the authors believe that such comprehensive methods are so complex due to several uncertainties. [Oldenburg *et al.*, 2009]

Oxand (an international engineering and consulting company specialized in industrial risk management) applies a classic risk management approach for storage (Identification, Estimation, Evaluation, Treatment), previously presented in Figure 1.13. For the identification of risks, FMECA (Failure Mode, Effects and Criticality Analysis) is used, which is a well-known classic method. For the risk estimation, they use the quantitative and qualitative methods to define the probability and severity of risks. The risk evaluation is carried out by ALARP (As Low As Reasonably Practicable) method. The treatment is categorized in four levels: risk control, spreading the risk over a time period, share the risk, and risk transfer. Oxand experts believe that many well-known methods could be used for Capture and Transport. [Chammas & Poupard, 2011]

Benson proposes to study lessons learned from analogous technologies in order to better understand the risks associated with CO_2 storage projects. She remarks three examples as the analogues of CO_2 storage: natural disasters like the catastrophic volcanic release of Lake Nyos in Cameroon, 1986, and the storage of natural gas and nuclear wastes. [Benson, 2002]

Perry has recently studied the experiences of natural gas storage industry and the potential application to CO_2 geological storage. He has reviewed the relevant literature and performed surveys/interviews with operators in Europe, Canada and the United States. *An important finding of this study is that only 10 of about 600 storage reservoirs operated in United States, Canada and Europe have been identified to have experienced leakage. Four due to cap rock issues, five due to well bore integrity, and one due to reservoir selection (too shallow)*. Monitoring the geological formation is the most significant factor that he mentions for controlling the risks. [Perry, 2005]

1.6.1.4 CTSC whole chain: available Risk Management approaches

As discussed before, a great number of risk management approaches cover one aspect of CTSC chain. However, there are examples in the literature that highlight the necessity of an integrative risk management method for CTSC.

Farret *et al.* underline the importance of developing an integrated approach in risk analysis of CTSC due to interdependency of four steps, i.e. Capture, Transport, Injection to the reservoir and Long-term Storage. [Farret *et al.*, 2009]

Gerstenberger *et al*. believe that a comprehensive risk assessment method does not yet exist for CTSC and needs to be developed. [Gerstenberger *et al*., 2009]

The (semi-)integrated studies that have been already carried out on CTSC risk management are as following:

GCCSI applies the Australian and New Zealand Standard for Risk Management (AS/NZS 4360: 2004) to define the likelihood and consequences of a set of extreme risks associated to integrated CTSC projects. Seventeen risks are identified with public, governmental/regulatory/policy, business case and technical nature. [GCCSI, 2009a]

Det Norske Veritas (DNV) has studied HSE issues related to large-scale capture, transport and storage of CO_2. In their study, an almost integrated analysis has been performed; hence capture, transport and injection phases are considered in the analysis (storage phase is not included). DNV method for risk assessment of large-scale CTSC projects is SWIFT (Structured What IF Technique) analysis. SWIFT analysis is an expert panel/workshop approach to identify potential hazards and uncertainties. Prior to the workshop, a questionnaire was sent to the stakeholders in order to gather their ideas about HSE issues regarding CTSC (from capture to injection phase). The participants have mentioned the lack of an integrated approach as a concern in HSE risk management of CTSC, an approach that takes into account CTSC whole chain [Johnsen *et al.*, 2009].

Another work on CTSC integrated risk analysis is the approach presented by Kerlero de Rosbo for the Belchatow project, in which Alstom was responsible to develop a CTSC plant for a coal-based power plant in Poland. Technical, financial, organizational, socio-political and regulatory risks associated with a large-scale CTSC project have been studied in that project. The deliverable was a risk register provided in panel discussions carried out to meet the project objectives. [Kerlero de Rosbo, 2009]

1.6.2 Requirement of a novel systemic approach for CTSC Risk Management

CTSC is a complex sociotechnical system which includes a technical system with three components of Capture, Transport and Storage. The social part of CTSC sociotechnical system involves an organizational structure containing a group of actors. The interface between organizational, human and technical aspects could initiate a failure in the system. In the succeeding part, we will recall the definition of system, complex system, and sociotechnical system.

Durand points out six definitions for system [Durand, 2010]:

1. System is an organized whole, made up of interdependent elements that can be defined as relative to each other according to their place in this whole. (definition of Ferdinand de Saussure, Swiss linguist)
2. System is a set of units and their mutual interrelations. (definition of Karl Ludwig von Bertalanffy, Austrian-born biologist)
3. System is a set of elements linked by a set of relationships (definition of Jacques Lesourne, French economist)
4. System is a set of elements in dynamic interaction which are organized based on a purpose. (Joël de Rosnay, French biologist)
5. System is a complex object, consisting of separate components interconnected by a number of relationships. (definition of Jean Ladrière, Belgian philosopher/logician)
6. System is a global unit organized by interrelationships between elements, actions or individuals. (definition of Edgar Morin, French philosopher and sociologist)

International Risk Governance Council (IRGC) defines a complex system as a *system composed of many parts that interact with and adapt each other. In most cases, the behavior of such systems cannot be adequately understood by only studying their component parts. This is because the behavior of such systems arises through the interactions among those parts*. Complex systems have some common characteristics including *Emergence, Non-linearity, Inertia, Threshold behavior, and Hysteresis and Path Dependency*. These characteristics lead to difficulties in anticipating and controlling system behavior. IRGC argues that *Adaptability* and *Self-organization* are other features of complex systems that *make risk emergence less likely*. □Emerging risk□ is defined as *one that is new, or a familiar risk that becomes apparent in new or unfamiliar conditions*. [IRGC, 2010]

A sociotechnical system is a system consisting of a technical part that is in interaction with a social part. The components of sociotechnical system include human beings (workers, managers and all the stakeholders of internal and external environment), an organizational structure and a technical section (including equipment, methods and tools) [Carayon, 2006]. These components are in interrelation with the external environment of the system. (Figure 1.16) [Samadi & Garbolino, 2011]

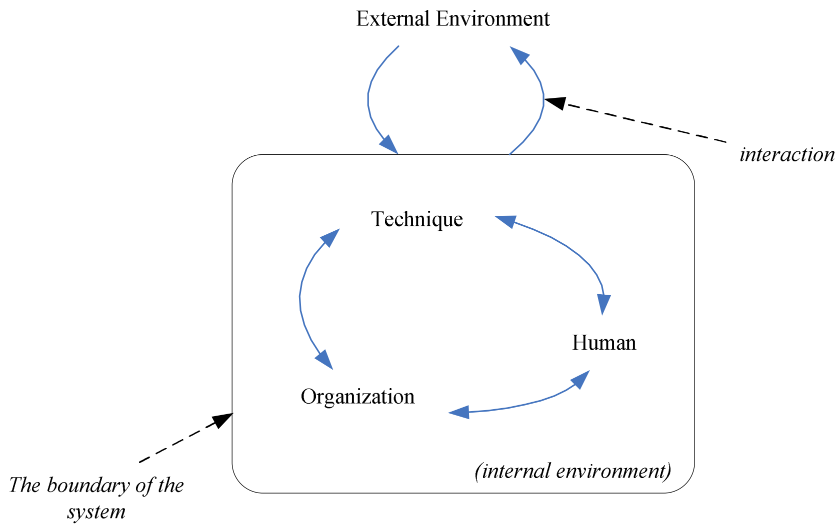


Figure 1.16: Model of a sociotechnical system [Samadi & Garbolino, 2011]

With the definitions provided in this section, we could consider CTSC as a complex sociotechnical system. As discussed in section 1.5.2, traditional risk management methods are inappropriate for such systems, and novel systemic approaches are required.

A systemic approach will be presented in subsequent chapters for CTSC risk management. The proposed approach is based on systems theory concepts, system dynamics and STAMP, which will be introduced in Chapter 2.

Summary, Chapter 1

In this chapter, the position of Capture, Transport and Storage of CO_2 (CTSC) in climate change mitigation was introduced. An overview of CTSC projects in the world was also presented. A section was devoted to the introduction of different Capture, Transport and Storage processes. Risks associated to each subsystem and the whole chain were presented. Risks related to the whole chain in a complex sociotechnical framework were classified in eight groups: Technical, Risks related to Project, Social, Policy/Strategy, HSE, Regulatory, Organizational/Human and Financial/Economic. Notions of risk and risk management were introduced, followed by a general recall of classic and modern risk assessment methods. This section includes accident models evolution, which is required to understand the necessity of proposing a systemic risk management framework for CTSC, as an emerging technology. In the last part, available risk management approaches for Capture, Transport and Storage were reviewed individually. Finally, integrated (systemic) approaches were argued as essential need of risk management for CTSC.

Résumé (French Summary of Chapter 1)

Dans ce chapitre, le rôle de la technologie de Captage, Transport et Stockage de CO_2 (CTSC) par rapport au changement climatique a été introduit et une vue d'ensemble des projets de CTSC dans le monde a été également présentée. Une partie a été consacrée à l'introduction de différents processus de Captage, Transport et Stockage de CO_2. Les risques associés à chaque sous-système (C, T et S) et à l'ensemble de la chaîne ont été présentés. Les risques liés au système global, considéré comme un système sociotechnique complexe, sont classés selon huit principales catégories. Ces catégories comprennent les risques techniques, les risques liés au projet, les risques sociaux, les risques politiques/stratégiques, les risques liés aux Santé, Sécurité et Environnement (SSE), les risques réglementaires, les risques organisationnels/humains et les risques financières/économiques. Les notions du risque et de la gestion des risques ont été introduites, suite à un rappel général des méthodes classiques et de celles plus récentes d'évaluation des risques. Cette partie inclut ainsi l'étude de l'évolution des modèles d'accident permettant de comprendre pourquoi une approche systémique de management des risques est indispensable pour le CTSC qui représente une technologie émergente. Dans la dernière partie, les méthodologies de gestion des risques disponibles pour le Captage, le Transport et le Stockage ont été étudiées individuellement. La conclusion propose que les approches intégrées (systémiques) sont essentielles pour la gestion des risques des activités de CTSC.

Chapter 2: Contribution of Systems Theory and System Dynamics to CTSC Risk Management

In this chapter, we will argue how systems theory, system dynamics, and STAMP (Systems-Theoretic Accident Model and Processes) approach can contribute to the risk management of CTSC projects. The chapter includes four sections:

The first section is devoted to the introduction of systems theory and system dynamics.

In section 2.2, a general review of system dynamics application fields is provided.

In the third section, current dynamics of CTSC technology are presented.

We will finally discuss how systemic approaches, and specially STAMP, could analyze the dynamics of CTSC.

2.1 Systems Theory and System Dynamics: Introduction and key concepts

2.1.1 Systems Theory

The modern concept of system emerged in the second half of the twentieth century in different scientific fields. Durand (2010) names five famous pioneers who invented the novel concept of system:

- Ludwig von Bertanlanffy (1901-1972), the Austrian biologist, who is the creator of “General Systems Theory”
- Norbert Wiener (1894-1964), American mathematician and professor at MIT (Massachusetts Institute of Technology), who applied the systems theory in control and communications engineering [Leveson, 2009]. His famous book is “Cybernetics”, published in 1948 [Wiener, 1948].
- Claude Elwood Shannon (1916-2001), American mathematician and telecommunication engineer, who has published “A mathematical theory of communication” in 1948. [Shannon, 1948]
- Warren Sturgis McCulloch (1898-1969), American neurophysiologist, who broadened his research in mathematics and engineering.
- Jay Wright Forrester (1918-), American engineer and professor at MIT, who developed the application of systems theory in the industrial dynamics and created System Dynamics.

Development of the modern systems theory was essentially localized in the United States. Nevertheless, in 1960s, 1970s the phenomenon was introduced out of the US, essentially by two publications: The limits to Growth, 1972 [Meadows *et al*., 1972] and Le macroscope, published in France in 1975 [De Rosnay, 1975].

Prior to the emergence of systemic thinking, occidental science was built on classic rationalism of Aristotle and Descartes. Durand (2010) cites four principal percepts which are sufficient for carrying out scientific research from Descartes's point of view:

- Accept nothing as a truth without having evidence
- Divide the problems in as much parts as possible in order to better resolve them
- Analyze our thoughts in order, starting from the ones that are easier to study
- Always have the most complete and general reviews to ensure that nothing is missed

A comparison of classic rationalism approach, which is based on Cartesianism (philosophical doctrine of René Descartes), and Systemic approach is presented in the following table:

Table 2.1: Classic Rationalism Approach vs. Systemic Approach (translated from [Durand, 2010; Le Moigne, 2006])

Percepts of Classic Rationalism Approach	Percepts of Systemic Approach
1. Evidence 2. Reductionist 3. Causality (linear reasoning) 4. Exhaustiveness	1. Relevance (regarding to the researcher) 2. Globalism (regarding the system's environment) 3. Teleological (searching the system behavior) 4. Aggregation (for a simplified representation)

There are four principal concepts in the systemic approach: interaction, totality, organization and complexity [Durand, 2010]:

- Interaction: means the mutual effect of system elements, comparing to the simple causal action of A on B in classic science. This notion leads us to the concept of feedback, which will be defined in section 2.1.2.
- Totality: the best and most ancient citation regarding this concept is the Blaise Pascal's (French mathematician, physicist, inventor, philosopher, religious thinker, and writer of the 17th century). He believes that it is impossible to know the parts without knowing the whole and to know the whole without knowing the individual parts.

- Organization: could be defined as a set of relations among the elements or individuals which forms a new unit, without necessarily the same qualities of the components.
- Complexity: Edgar Morin is one of the pioneers in complexity. He believes that complexity refers not only to the quantity of elements and interactions in the system, but also to the uncertainties, disinclinations and unpredictable phenomena (the concept of "emergence" in complex systems which was introduced in Chapter 1, section 1.6.2). Morin states that complexity always deals with hazard [Morin, 2005, p.49]. This idea directs us to the application of systemic approach in the field of risk management which will be developed in sections 2.2 and 2.4.

Hardy cites five characteristics of systems, which are more or less similar to the abovementioned concepts. These characteristics, cited from [Gharajedaghi, 2006] consist of Interaction, Structure, Emergence, Auto-organization and Feedback. [Hardy, 2010]

2.1.2 System Dynamics

System dynamics has its roots in control engineering, cybernetics and general system science. [Fuchs, 2006]

System dynamics is a methodology to understand the structure and behavior of complex systems, created during the mid 1950s by Jay W. Forrester in the Massachusetts Institute of Technology (MIT). He defines system dynamics as a combination of theory, methods and philosophy required to analyze the behavior of systems. [Forrester, 1991]

System dynamics is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering. [Sterman, 2000, p.5]

The advent of system dynamics was a pencil and paper simulation of General Electric inventory control system. Forrester showed by this hand simulation that the source of instability in General Electric employment was due to internal structure of the company not to external forces such as the business cycle [Forrester, 1996; Radzicki & Taylor, 1997].

Thereafter, system dynamics has been applied in various fields from management to environmental change, politics, economic behavior, medicine, engineering, and recently for analyzing accidents and risks [Forrester, 1991; Leveson, 2004a,b; Stringfellow, 2010; Garbolino *et al.*, 2009; Garbolino *et al.*, 2010; Dulac, 2007]. The application disciplines of system dynamics will be discussed in section 2.2.

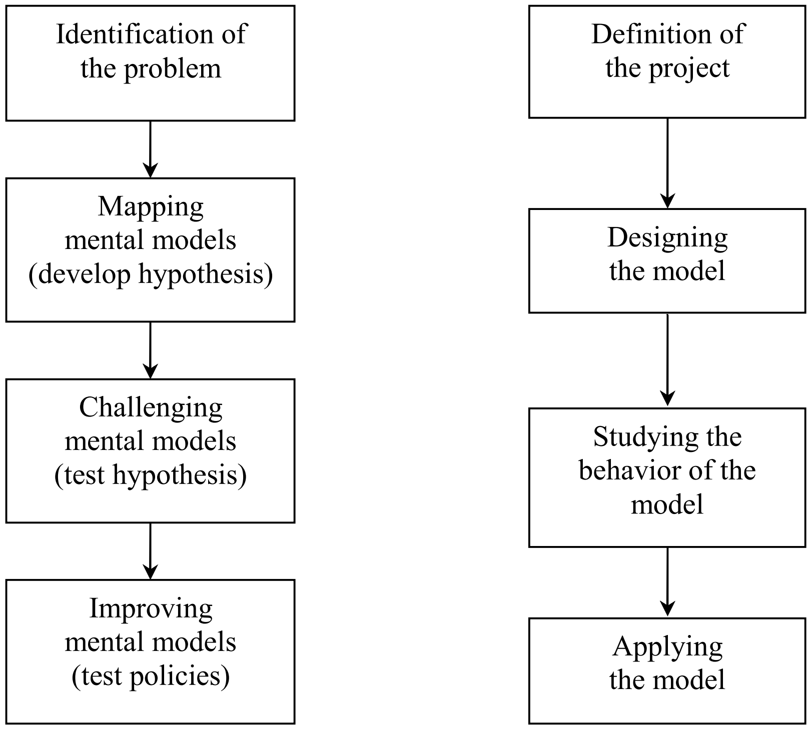
Models and modeling are the most essential concepts in system dynamics. Models are simplifications of reality which help people to clarify their thinking and improve their understanding of the world. Paul Valéry (French writer, poet, philosopher and epistemologist) believes that models are the only bases of our thinking [Durand, 2010]. *All human beings have a mental representation of the systems around them, such as families, universities, cities, etc. These mental models are flexible and rich in detail, but they are often fuzzy, incomplete and imprecise. That's why system dynamicists propose to decision-makers to apply system dynamics to map out their mental models on the computer and follow the evolution of the system through the computer model* [Radzicki & Taylor, 1997]. The process of modeling a system and studying its behavior over time is termed "dynamic modeling".

As Forrester affirms, an industrial activity is made up of six interconnected networks: materials, orders, money, capital equipment, personnel and information. The information network interconnects the other five. [Forrester, 1968]

General steps of dynamic modeling presented by Forrester (1968) are as follows:

1. Identify the problem and the questions to be answered
2. Gathering required information (for a production-distribution system, these information include organizational structure, delays in decisions and actions, policies governing purchases and inventories)
3. Establishment of mathematical description of the system
4. Simulation (tracing of a specific time history)
5. Interpretation of the results
6. System revision (redesign of system structures and policies)
7. Reiterated experimentation

The process of dynamic modeling is illustrated in Figure 2.1:



adapted from [Radzicki & Taylor, 1997] adapted from [Durand, 2010]

Figure 2.1: Dynamic modeling process

Figure 2.1 should be improved by integrating both processes and adding a feedback from the end of the process to mapping mental models. In reality, the mental models are changing based on the feedbacks from the results of their application. The modified version of dynamic modeling process is shown in Figure 2.2. The feedback is presented differently by [Sterman, 2000] in Figure 2.3.

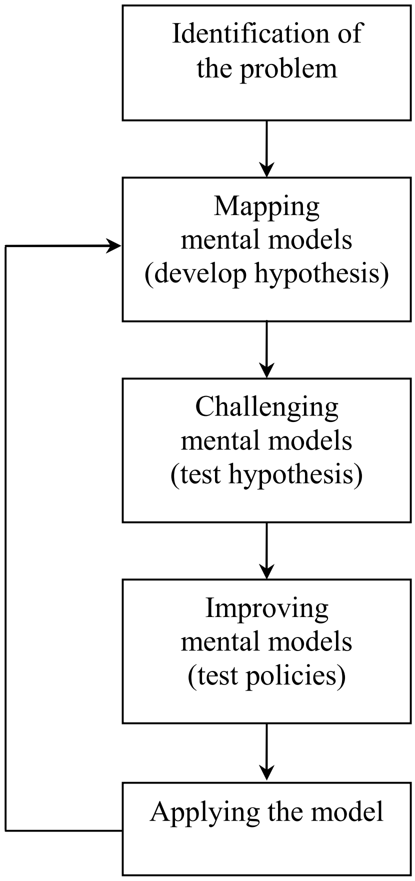


Figure 2.2: Improved dynamic modeling process

System dynamics modeling consists of four main concepts of Variable, Feedback (loop), Causal Graph and Delay. These notions are introduced in the subsequent paragraphs.

Variable: Each element of the system that we put in the model could be a variable. There are three types of variables: Stock, Flow, and Auxiliary (Control) variables.

- Stock (or Level): is an accumulation within the system, for example inventories, goods in transit, bank balances, factory space and the number of employees [Forrester, 1968]. The quantity of stock is the integral of difference between its outflow and inflow.
- Flow (or Flow Rate or Rate): is another element of a model structure that defines the flows between the stocks in the system. [Forrester, 1968]

The following equation shows the mathematical relation between the stocks and flows:

$$levels_t = \int_0^T rates_t dt \qquad \text{or} \qquad \frac{d}{dt} levels_t = rates_t$$

According to Forrester, *Stocks and Flows exist in all six networks that may constitute a system: materials, orders, money, personnel, capital equipment and information* [Forrester, 1968].

One of the most challenging parts of dynamic modeling is to correctly distinguish the stocks and the flows. As Forrester proposes, in order to determine whether a variable is a stock or a flow, we should see whether or not the variable would continue to exist in the system. The variable which will continue to exist is a stock (such as inventories of a warehouse). Flow is the variable that could be stopped (like receiving and shipping goods).

- Auxiliary (Control) variable: is a variable that is *computed from other variables at a given time. Auxiliaries are typically the most numerous variable type*. [Vensim, 2010, p.22]

Feedback and Feedback Loop: *From a system dynamics point of view, a system can be classified as "open" or "closed".* Open systems are the ones in which the outputs have no influence on the inputs of the system. In closed systems, the outputs do have influence on the inputs. Most of the systems in the real world are closed systems and the effect of output on input is called Feedback. [Radzicki & Taylor, 1997]

There are two types of feedback loops in a closed system: positive (or reinforcing) and negative (or balancing) loops. Positive feedback loops are the ones which *destabilize the system and cause them to run away from their current situation* whilst negative feedback loops stabilize the system [Radzicki & Taylor, 1997]. In a positive feedback loop, the variables change in the same direction, whereas they will change in the opposite direction in a negative feedback loop. In other words, in a positive feedback, if the first variable increases, the second variable will be increased (the same direction as the first variable). However, in a negative feedback, an increase in the first variable leads to a decrease in the second variable (the opposite direction).

Negative and positive feedback loops in a complex system result in the synchronization of the system and help the system to keep its dynamic equilibrium. Feedback loops depend on a series of decisions from different endogenous and exogenous actors [Louisot, 2004, p. 65].

Sterman (2000) argues that sometimes our decisions may have unexpected effects and change the evolution direction of systems. He believes that *unexpected dynamics often lead to policy resistance. One cause of policy resistance is our tendency to interpret experience as a series of events*. Since we have an "*event-oriented worldview*", we have an "*event-oriented approach to problem solving*". However, *policy resistance arises because we often do not understand the full range of feedbacks operating in the system*. Sterman reasons that the dynamics of all systems arise from the interactions of feedback networks. He illustrates a "*holistic*" feedback schematic of the real world, as a system, and our decisions, mental models and strategies as following:

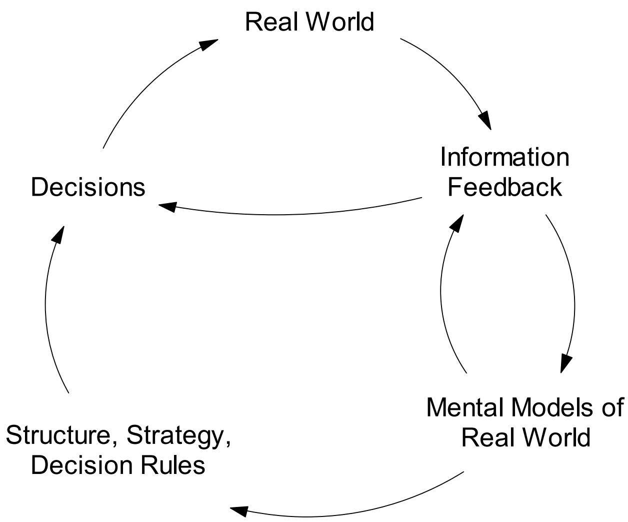


Figure 2.3: Double loop learning in the real world [Sterman, 2000]

Information feedback from the real world affects not only our decisions, but also our mental models. As a result, we will change the structure of our systems, decision rules and our strategies. [Sterman, 2000, pp.5-19]

In order to better understand the concepts of stock, flow and feedback, we could recall the example of [Dulac *et al.*, 2007], illustrated in Figure 2.4.

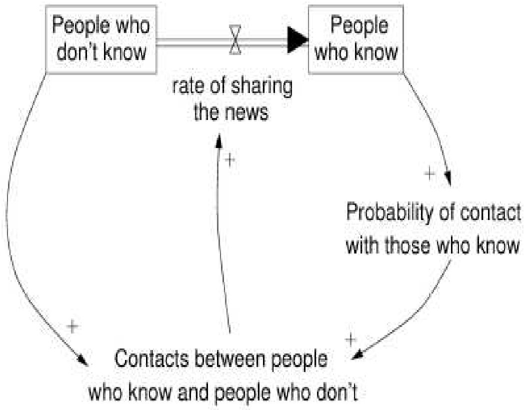


Figure 2.4: An example of stock-flow-feedback loop structure [Dulac *et al.*, 2007]

The example shows the flow of information through a population over time. At the beginning, only 1 person is aware of the news and the other 99 persons are unaware. Therefore, the model consists of two stocks: "*People who know*", with the initial value of 1 and "P*eople who don't know*", with the initial value of 99. The "*rate of sharing the news*" is the flow between the two stocks of the system, which depends on the number of "*contacts between people who know and people who don't*". The + signs in Figure 2.4 show the positive feedback loops of the system. The valve sign in Figure 2.4 (⧖) is indicative of "decision function" by Forrester. Decision functions determine the rate of flow between two stocks.

To understand the concept of negative feedback, we should review another example (Figure 2.5). If we consider the balance between gasoline consumption and car pools, in case of an increase in gasoline consumption, gasoline price will increase. The increase of gasoline price will motivate people to join car pools. As a result, the number of vehicles and gasoline consumption will be reduced. This negative feedback loop is illustrated in Figure 2.5.

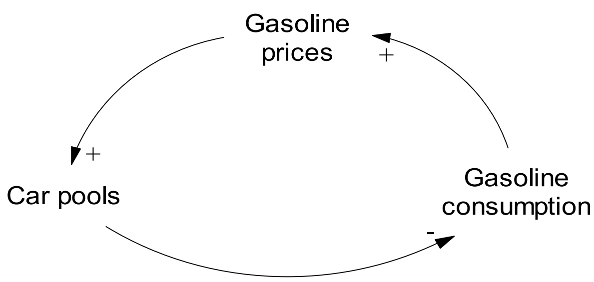


Figure 2.5: An example of negative feedback loop [Radzicki & Taylor, 1997]

Causal graphs: are the diagrams containing the network of feedback loops, or the interactions of the system variables.

The examples concerning CTSC system will be presented in Chapter 3.

Delay: is another important concept in system dynamics. Radzicki and Taylor explain the concept of delay by the fact that *events in the world do not occur instantaneously. Instead, there is often a significant lag between cause and effect. The longer the delay between cause and effect, the more likely it is that a decision maker will not perceive a connection between the two*. [Radzicki & Taylor, 1997]

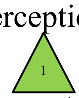
Several software packages are available for dynamic modeling such as VENSIM®, STELLA®, GOLDSIM®, ITHINK® and POWERSIM®. Models presented in the current report have been developed by VENSIM®.

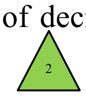
Richardson (2011) believes that □endogenous point of view□is in fact the foundation of system dynamics. In this viewpoint, system is considered as cause. *System dynamicists use system thinking, management insights and computer simulation to:*

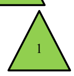
- *hypothesize, test and refine endogenous explanations of system change, and*
- *use those explanations to guide policy and decision making*

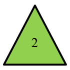
Sterman asserts Richardson idea and mentions that *system dynamics seeks endogenous explanations for phenomena*. □*Endogenous*□ is defined as □*arising from within*□ by [Sterman, 2000, p.95].

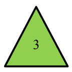
Richardson remarks the concept of agency in system dynamics by asking: *Who are the actors in the dynamics of a complex system and how do their perceptions, pressures, and policies interact?*

Four possibilities are conceivable between the perceptions of decision makers and the reality (Figure 2.6). In the first and second ones (

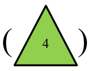
and 

), the decision maker perceptions match the reality. In the first case (

), decision makers have an exogenous view about a phenomenon which is exogenously created. In this case, the best choice is to *accept the fate, predict and prepare for whatever we believe is coming*. In the second case (

), decision makers have a right endogenous view of an endogenous phenomenon. This is the case that could be well understood by the feedback notion in system dynamics. As shown in Figure 2.6 by smileys, this case is the most favorable one. In the third box of Figure 2.6 (

), the situation is externally created. However, we are attempting to find endogenous explanations to control the

situation. The effort fails as our perception is not in conformity with the reality. The fourth option (
) is the worst one. The situation causes are in fact endogenous, while we are finding external explanations. Therefore, *we are confused and misguided, and we will misguide others*. The conclusion is that having an endogenous point of view about all phenomena is more advantageous. [Richardson, 2011]

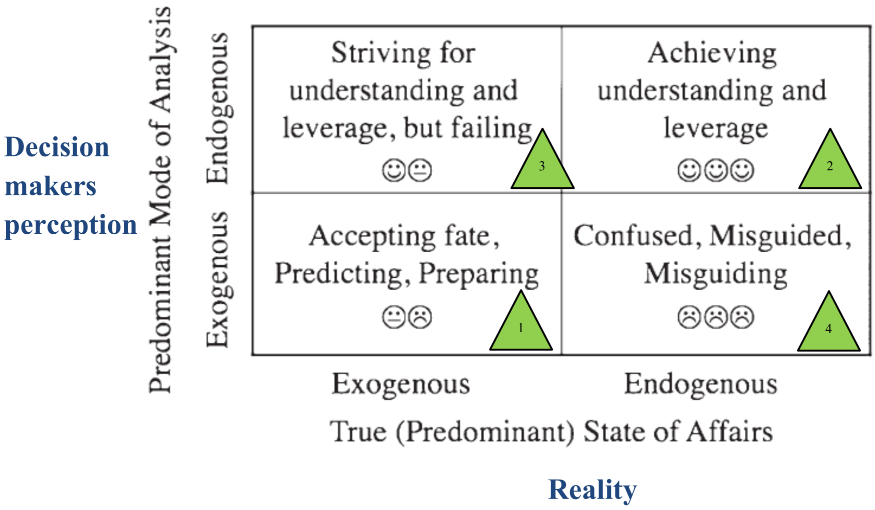


Figure 2.6: Exogenous and Endogenous perceptions versus the corresponding reality [Richardson, 2011]

The significance of endogenous viewpoint has been also supported by Stave, who has used system dynamics to help a group of stakeholders working on transportation and air quality problems. She highlights the importance of focusing on a problem in system dynamics by asking the question *what is the problematic behavior or behaviors we are trying to change?*

The endogenous position is affirmed by inquiring *how does the system generate the problematic behavior?* [Stave, 2002]

2.2 Application fields of System Dynamics

Winch (2000) affirms that system dynamics is not only a theory, but also a *practical tool*. He argues that qualitative or “*soft*” applications of stock-flow and / or causal diagrams are as useful as simulation applications. Qualitative use allows developing feedback networks and understanding the system behavior.

Winch has reviewed the articles published by System Dynamics Review [(1)] in the period of 1995-2000. In this period of time, he was the Executive Editor of the journal.

The application contexts of the reviewed articles include Business, Public sector, Social and macro-economic systems, and Natural/technological systems (It should be noted that the application field of one third of the published articles were not specified). The majority of the papers concerned business applications (Strategy and Policy). Public sector and Social / macro-economic issues come next after. The author concludes that system dynamics approach has been also widely applied in management, even if the studied sample (System Dynamics Review) does not cover all the applications of system dynamics. [Winch, 2000]

Fuchs cites social sciences, including economics and management, and environmental science as the application fields of system dynamics. It is also a part of some training courses, such as biology and psychology, in the schools. Nevertheless, system dynamics has not been used in physics and engineering. Fuchs argues that system dynamics is a useful, simple and powerful modeling approach that should be added to the pedagogical system of science and engineering. [Fuchs, 2006]

Forrester, the pioneer of system dynamics, made a review of system dynamics status in the past 50 years and proposed some prospects for the next fifty years. He affirms that the applications of the past 50 years were focused on management, and less on medicine, economics, government policies, and international politics. He believes that we need to *move sufficient understanding of the behavior of complex systems into the public sector*. Then we can gradually integrate system dynamics in the university programs. Forrester cites global warming as a *hot topic* on which *debates are about how to reduce symptoms rather than eliminate causes*, while *system dynamicists must go beyond the symptoms of trouble and identify the basic causes*. [Forrester, 2007]

(1) Official journal of the System Dynamics Society, published by John Wiley and Sons, http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1727

Garbolino *et al.* have recently introduced three fields for which system dynamics has been applied. These fields include supply chains, risk management and environment, and understanding the occurrence of accidents [Garbolino *et al.*, 2010]. In the following paragraphs some examples are presented for each category.

A reference for system dynamics use in supply chains is the work of Pierreval *et al.* on the simulation of an automobile industry supply chain, where the authors apply Forrester's method of modeling to identify the elements of the system and their interconnections through material and information flows in order to study the behavior of the supply chain over time [Pierreval *et al.*, 2007].

Santos-Reyes and Beard [Santos-Reyes & Beard, 2001; Santos-Reyes & Beard, 2008] apply system dynamics approach to present a safety management system. For Ouyang *et al.*, system dynamics and specifically STELLA® software is a tool to model the consequences of industrial activities on the environment [Ouyang, 2002; Ouyang *et al.*, 2007]. Another example is the thesis of Reap [Reap, 2004] which models the impacts of industrial activities on the ecosystem. Cooke and Rohdeler studied incident's emergency situation with a systemic approach. They proposed a training systemic modeling to avoid critical situations [Cooke & Rohdeler, 2006].

As introduced by Garbolino *et al.* (2010), a new application domain of system dynamics is risk and safety management. System dynamics could be a support for decision making. From this point of view, the application of system dynamics in risk management could help the decision makers to improve their understanding of safety control tools and to determine whether the prevention or protection barriers are sufficient and appropriate.

Garbolino *et al.* (2010) have presented a dynamic risk analysis approach for a Cl_2 storage and transport unit (to a plastic production plant). Their approach includes four steps. The first step is to construct the structure of the system in the form of a dynamic model (stock-flow-feedback structure), develop the causal diagrams which illustrate the interactions among the variables of the system, and define the variables of the system.

Authors have selected STELLA® software to perform dynamic modeling. In next step, potential failures of the system are studied with HAZOP (Hazard and Operability) method. In this phase, the failures as well as their causes and consequences are identified.

Afterwards, the failure consequences are modeled. The PHAST software is applied for this purpose to evaluate the effects of failures like toxic waste and overpressure on human beings and equipment. Finally, they go back to dynamic modeling environment in order to evaluate whether the available prevention and protection barriers are efficient. If not, new barriers could be recommended to be added in the system. Their approach is summarized in Figure 2.7.

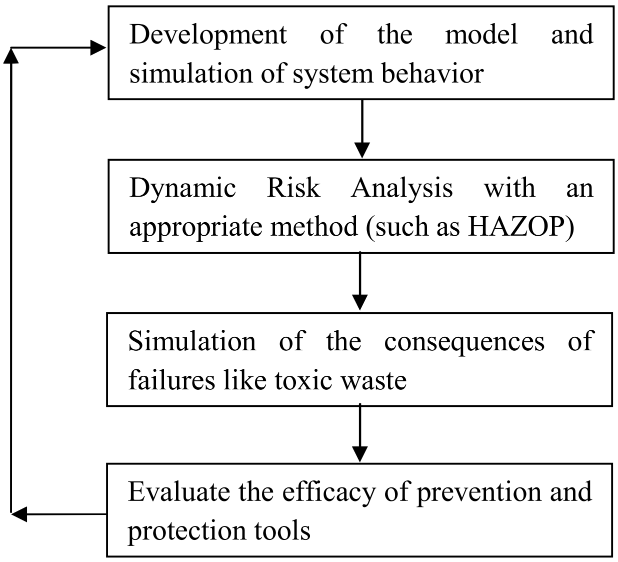


Figure 2.7: General steps of dynamic risk analysis for an industrial plant [Garbolino *et al.*, 2010]

As previously mentioned in Chapter 1, section 1.5.2, systemic accident models are the latest generation of accident models, which give prominence to the dynamic and nonlinear characteristics of systems. STAMP (Systems-Theoretic Accident Model and Processes) model, developed by Nancy Leveson at MIT (Massachusetts Institute of Technology), is one example already introduced in section 1.5.2.

Leveson affirms that to prevent accidents in complex systems we require using accident models that include social system as well as the technology and its underlying science. STAMP accident model is created based on the idea which had been previously proposed by Rasmussen in 1997 [Leveson, 2004a]. Rasmussen argues that complex sociotechnical systems have been usually modeled by decomposition into separate components [Rasmussen, 1997]. Decomposition is possible if we ignore the interactions of components, and the associated feedback network.

Leveson believes that safety is an emergent property of systems, and can only be determined in the context of the whole (entire components of the system) [Leveson, 2009]. With the same reasoning, risks are also the emergent properties of system. Therefore, risks have to be assessed by taking into account the context in which they are generated.

Risk management could be considered as a means of control that should be able to propose a control structure for the whole system.

STAMP has been applied in several fields of study. Dulac has proposed a framework for dynamic safety and risk management modeling in complex engineering systems. He has focused on using the concepts of system dynamics modeling in STAMP. The application of the new framework has been presented for two projects of NASA (US National Aeronautics and Space Administration) [Dulac, 2007]. Stringfellow has recently proposed an accident and hazard analysis approach for human and organizational factors based on STAMP. She has presented some guidewords for human and organizational decision making [Stringfellow, 2010]. The guidewords are in fact the prevention and protection barriers, comparable with Basic Risk Factors of [Groeneweg, 2002] and Common Performance Conditions of [Hollnagel, 1998; Hollnagel, 2004].

Organizational and human factors are taken into account in the approach of Leveson and her team (e.g. Dulac and Stringfellow), while the work of Garbolino *et al.* (2010) deals only with the technical constituents of sociotechnical system.

More details on STAMP will be provided in section 2.4.2.

2.3 Current dynamics of CTSC

Dynamic complexity arises because of certain characteristics of systems, and among others because systems are dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent and self-organizing [Sterman, 2000].

Several sorts of dynamics are involved in CTSC current context. The main categories of dynamics are as following:

2.3.1 Dynamics of climate / atmosphere

The temperature of the earth's surface is increasing, mainly because of anthropogenic greenhouse emissions, which have been growing exponentially since the beginning of the industrial age. Greenhouse gases, such as CO_2, absorb a part of the energy radiated by the earth. Therefore, the amount of energy radiated back by the earth into the atmosphere will be less than the insolation. Consequently, the earth's surface temperature increases [Sterman & Sweeney, 2002].
Nevertheless, there are controversial ideas on the sources of global warming. Some have an endogenous view, and believe that human activities are responsible for global warming. From the contrary exogenous point of view, the increase of CO_2 concentrations and global temperature is part of a natural phenomenon [Richardson, 2011]. The endogenous viewpoint on the climate dynamics explains the necessity to mitigate industrial CO_2 emissions. CTSC is one of the mitigation options.

CO_2 annual emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 gigatonnes (Gt) [IPCC, 2007, p.14].
Future levels of global GHG emissions are a product of very complex, ill-understood dynamic systems, driven by forces such as population growth, socio-economic development, and technological progress among others, thus making long-term predictions about emissions virtually impossible. The Intergovernmental Panel on Climate Change (IPCC) has developed some scenarios to show how driving forces may influence future emissions. [IPCC, 2000]
Dynamics of global temperature rise and atmospheric CO_2 concentrations are presented in Figure 2.8:

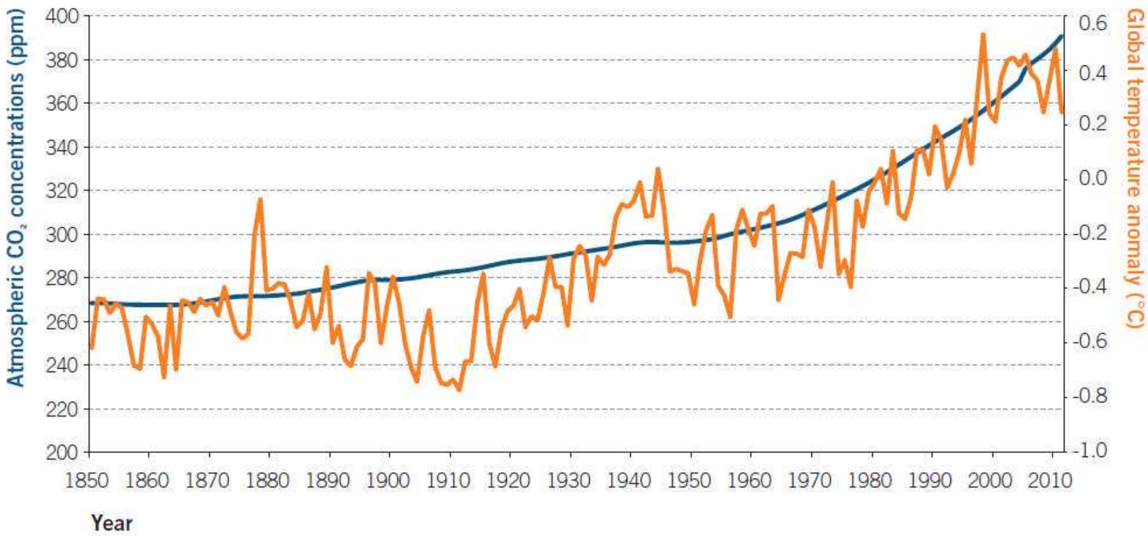


Figure 2.8: Global CO_2 atmospheric concentrations and temperature [GCCSI, 2011a]

2.3.2 Dynamics of subsurface

Hamblin and Christiansen define a dynamic system as a system which is in motion, when material and energy change from one form to another.

There are two types of systems in geology:

- A closed system that exchanges only heat (no matter) with its environment
- An open system that exchanges both heat and matter with its surroundings

Most geological systems are open systems, in which matter and energy freely flow across the system s boundaries. Therefore, materials on and in earth are changed and rearranged. The direction of change in a dynamic geological system, and generally in natural systems is towards a state of equilibrium. *The equilibrium is a condition of the lowest possible energy, or a condition in which the net result of the forces acting on a system is zero*.

Hydrologic system and tectonic system are the two main geologic systems. Major processes and elements of hydrologic and tectonic systems are illustrated in Figures 2.9 and 2.10 respectively.

[Hamblin & Christiansen, 2004]

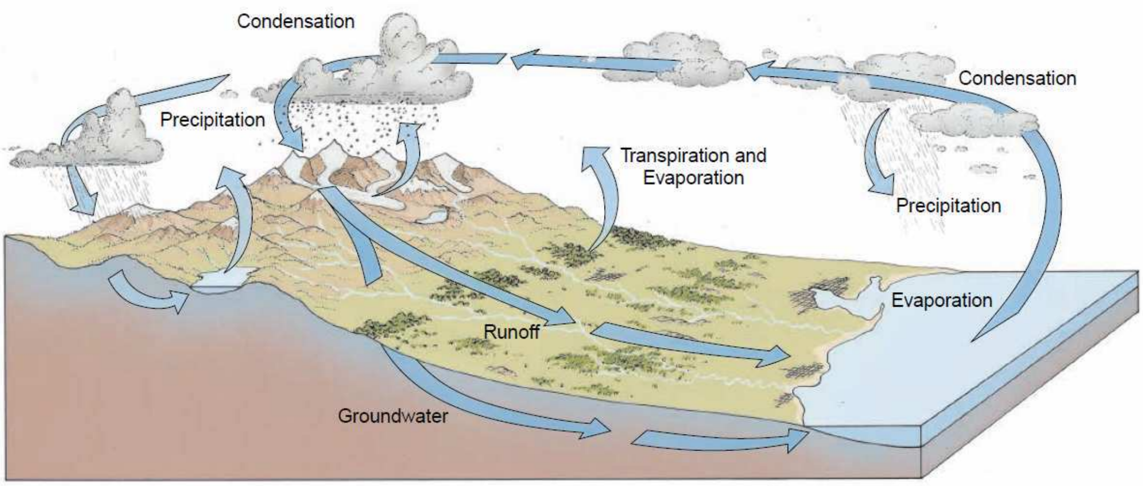


Figure 2.9: The circulation of water in the hydrologic system [Hamblin & Christiansen, 2004]

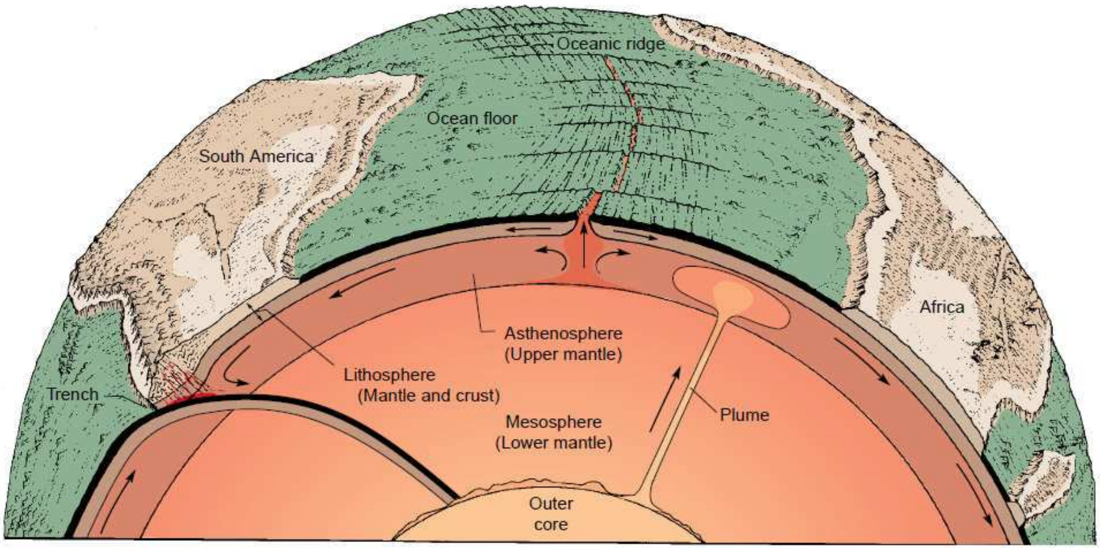


Figure 2.10: The tectonic system [Hamblin & Christiansen, 2004]

Most of the heat released from earth is generated by radioactive decay of three elements found in small quantities in almost all rocks: potassium, uranium and thorium. The heat is created when small quantities of matter are converted to energy. [Hamblin & Christiansen, 2004]

The geological environment, where CO_2 is injected and stored, is dynamic. The variations are under control by different modeling tools. The purpose is to make sure that the injected CO_2 will be remained isolated from the other compartments of the geological formation above the caprock (low-permeable geological layer that assures the sealing of CO_2 injection reservoir).

2.3.3 Dynamics of project

Project is the third aspect for which dynamics could be studied. CTSC projects have some common points with other industrial projects. There are also some specific characteristics, since CTSC is a novel technology and several actors and stakeholders are engaged in the development process of the technology.

Typical project dynamics, which are subject of several studies, include project staffing and productivity [Lyneis *et al.*, 2001]. However, stakeholders and project phases dynamics are other aspects of project dynamics. Stakeholder dynamics is defined as the potential complex behavior of stakeholders interacting over time. Interactions of stakeholders with different goals and perceptions of the system generate essential feedback effects within the system [Richardson & Andersen, 2010]. Several stakeholders are involved in CTSC projects. Governments (national and local), project developers, local public, municipal and regulatory authorities, and non-governmental organizations (such as environmental organizations) are the main stakeholders of a CTSC project. The second aspect of project dynamics is related to the project phases. The major phases of a CTSC project consist of Opportunity, Definition and Planning, Engineering, Construction, Operation (Injection of CO_2), and Post-injection (Monitoring). These phases have been already defined in section 1.4.2.4.

A timeline has been proposed by CCP (CO_2 Capture Project) for CO_2 Storage life cycle. The timeline is available in Figure 2.11.

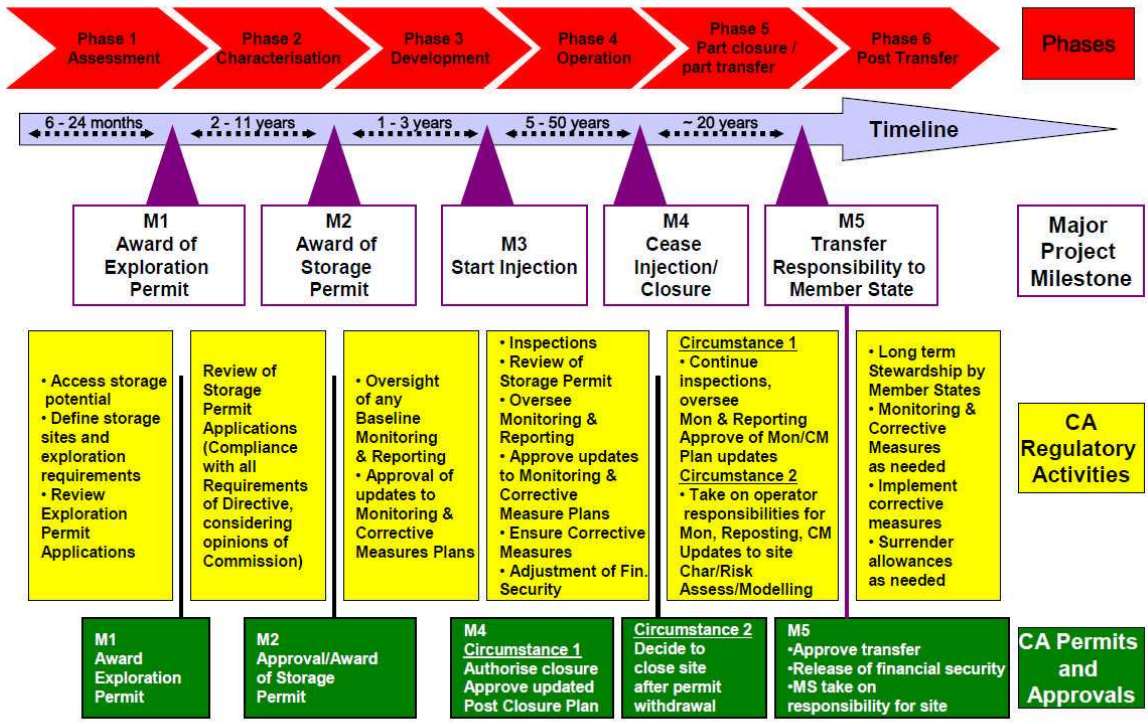


Figure 2.11: Summary of CO_2 Storage Life Cycle Phases and Milestones [CCP, 2010]

2.3.4 Dynamics of risks

IRGC (2010) has recently published the main factors from which risks can emerge. The report is focused on complex systems and emergence of systemic risks (as explained in sections 1.5.2 and 1.6.2).

IRGC argues that emerging risks are dynamic, since the systems are regularly adapting themselves to perturbations. *Some emerging risks lessen over time while others become worse than anticipated*. Therefore the consequences of emerging risks are not easily predictable. Furthermore, time delays between the perturbations, system responses and the internal/external impacts complicate the identification of emerging risks.

"Positive feedback" is one of the factors that could lead to the emergence of systemic risk. When the system response to a perturbation creates amplifications and destabilizes the system, a positive feedback is present. The notion of feedback (positive and negative) has been explained in section 2.1.2. Positive feedbacks tend to be destabilizing. Hence, they can *potentially increase the likelihood or consequences of the emergence of a new, systemic risk. It is therefore important for analysts to identify feedback dynamics (both positive and negative) that are occurring in a system, and* *assess their function and their relative balance (if their positive or negative dominate) in order to better anticipate when risks might emerge or be amplified.* [IRGC, 2010]

Rodrigues believes that risks are dynamic events. Risk dynamics are generated by a network of feedback loops in the project. He affirms that the management needs to have a systemic view to understand why risks emerge, because risks have a systemic nature [Rodrigues, 2001].

Current dynamics of CTSC were reviewed in this section. In the next part we will discuss how these dynamics could be studied and analyzed using systemic approaches.

2.4 Contribution of Systemic Approaches and System Dynamics to study the dynamics of CTSC

CTSC is a complex sociotechnical system, including three technical components of Capture, Transport and Storage, and an organization structure containing a group of actors [Samadi & Garbolino, 2011].

Available lessons learned from CTSC projects confirm that the feedback loops of different types of risk are significant in the development process of projects. Technical aspects of long-term safety of CO_2 storage have been always at the heart of risk assessment studies. However, technical risks are continually in inter-relation with other aspects of risk.

At the present time, the main question about CTSC is whether the technology will be developed progressively up to commercial scales. According to the available statistics on CTSC projects all around the world, only fourteen large scale integrated projects are currently in operation or construction. The other sixty projects are under identification or finalization of scopes and execution plans [GCCSI, 2011a]. (refer to Figure 1.3)

In the current thesis, we focus on modeling risks of CTSC projects development using a systemic approach. In other words, dynamics of project and risks are under study.

The question is how dynamics of risks affect dynamics of CTSC projects, and how interconnections of stakeholders and associated risks could result in the success or failure of a CTSC project progress. If we rephrase the goal in system dynamics language, the problem we are modeling is that some particular CTSC projects are not successful to be developed.

Lyneis and Ford mention four groups of project structures for which system dynamics has been applied. The structures include:

- Project features (development processes, resources, managerial mental models and decision making)
- Rework cycle
- Project control
- Ripple effects (such as fatigue, communication difficulties, and experience) and knock-on effects (such as hopelessness and morale problems) [Lyneis & Ford, 2007]

A methodology is developed based on STAMP approach to model the structure of safety control in CTSC projects, and analyze the feedback network dynamics of CTSC project risks.

To understand how STAMP, as a systemic approach, could contribute to study the risks of CTSC projects, we will firstly recall an overall view of risk and safety management approaches development in section 2.4.1. Details and examples of STAMP will be presented in section 2.4.2.

2.4.1 Evolution of risk / safety management approaches

As previously explained in Chapter 1, traditional risk analysis methods are based on sequential accident models, and therefore not appropriate for sociotechnical complex systems.

Safety management approaches have evolved based on the lessons learned from industrial accidents (Figure 2.12).

Until 1950s-1960s, safety was considered as a technical problem. Therefore, safety management was based on the improvement of technical systems reliability. From 1960s, technical issues were not sufficient to explain the accidents. Human errors are then brought in safety management approaches. By mid 1980s, lessons learned from industrial disasters such as Three Miles Island, Bhopal, Chernobyl and Challenger, highlighted the incomprehensiveness of human errors for analyzing accidents. According to Cambon, the lessons learned affirm that human errors could not be disconnected from the organizational context in which they had been generated. Hence, in 1980s-1990s, the human error is recognized as a consequence of the organizational problems. Cambon explains that the organizational approaches are characterized to be linear and epidemiological (as discussed by [Hollnagel, 2004]). Systemic or inter-organizational age emerged at the beginning of the twenty-first century in order to answer to this weak point in the precedent (organizational) age. [Cambon, 2007]

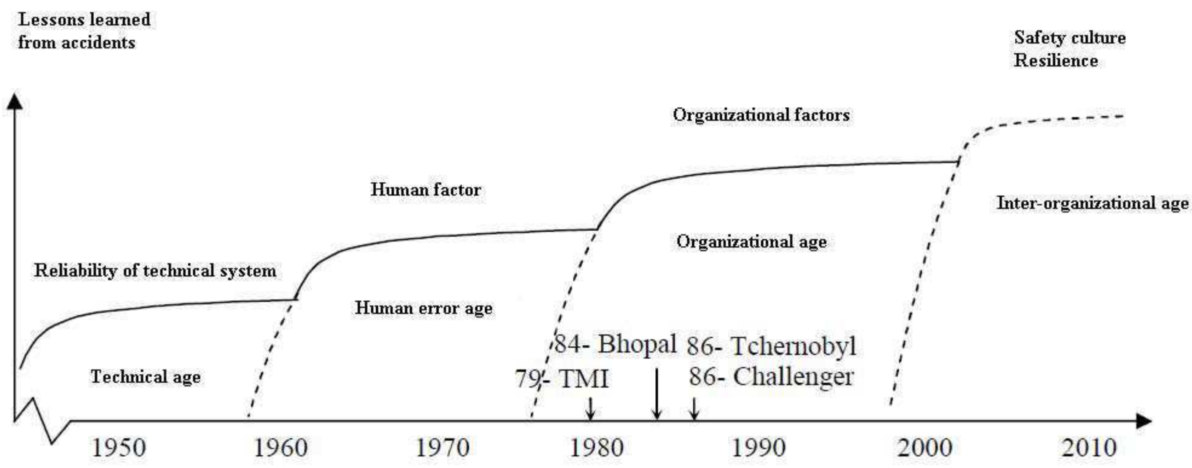


Figure 2.12: Evolution of safety management approaches (translated from [Cambon, 2007]) (originally adapted from Groeneweg, 2002; Wilpert & Fahlbruch, 1998)

Cambon intended to set off the significance of human and organizational factors in the management of safety within industries. However, it does not mean that technical issues have been completely removed from the causes of recent accidents since the technical age is terminated. This idea is supported by BARPI (Bureau d'Analyse des Risques et Pollutions Industriels). BARPI is the French office of Risk Analysis and Industrial Pollution, created in 1992, which is assigned to gather and analyze the information associated to industrial accidents. [BARPI, 2012]

In order to give a better structure to the Cambon's schematic (Figure 2.12), and show the complementary evolution of the approaches, it is proposed to illustrate the evolution as shown in Figure 2.13.

Figure 2.13 provides a clearer vision of the fact that Technical, Human and Organizational factors of safety are always in interconnection, and they cannot be disconnected through the evolution of approaches.

The funnel represents the systemic age, which includes all the three previous periods (organizational, human and technical). The arrows show the inter-relations of the three first ages.

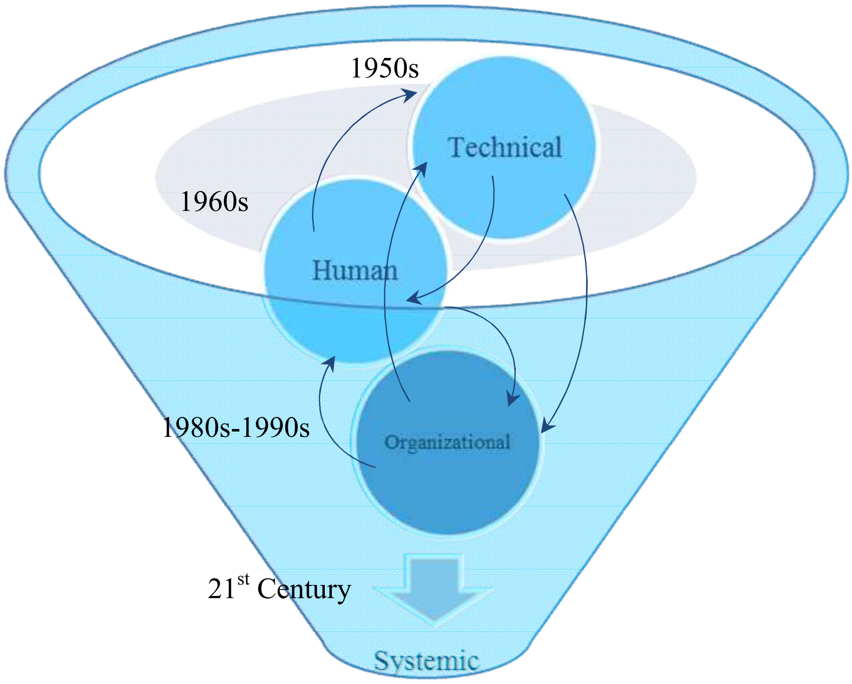


Figure 2.13: Evolution of safety management approaches, an improved proposition

2.4.2 STAMP contribution to CTSC risk management

At the end of section 2.2, we introduced the STAMP approach. Major concepts and some examples of this accident model are presented in this section.

Leveson's approach has its roots in the control theory. Leveson presents three main concepts in STAMP model. These concepts are: safety constraints, hierarchical control structures and process models.

Safety constraint is a major notion in STAMP. Leveson argues that *events leading to losses only occur because safety constraints were not successfully enforced*. Therefore, *we first need to identify the safety constraints to enforce and then to design effective controls to enforce them*. [Leveson, 2009]

Hierarchical control structures are the basis of systems in systems theory. Mutual feedbacks of controllers (each level of hierarchical control structure) lead to the improvement of maintaining safety constraints. Leveson proposes a general model of sociotechnical system control based on the model previously presented by Rasmussen. Models of Rasmussen and Leveson are illustrated in Figures 2.14 and 2.15 respectively.

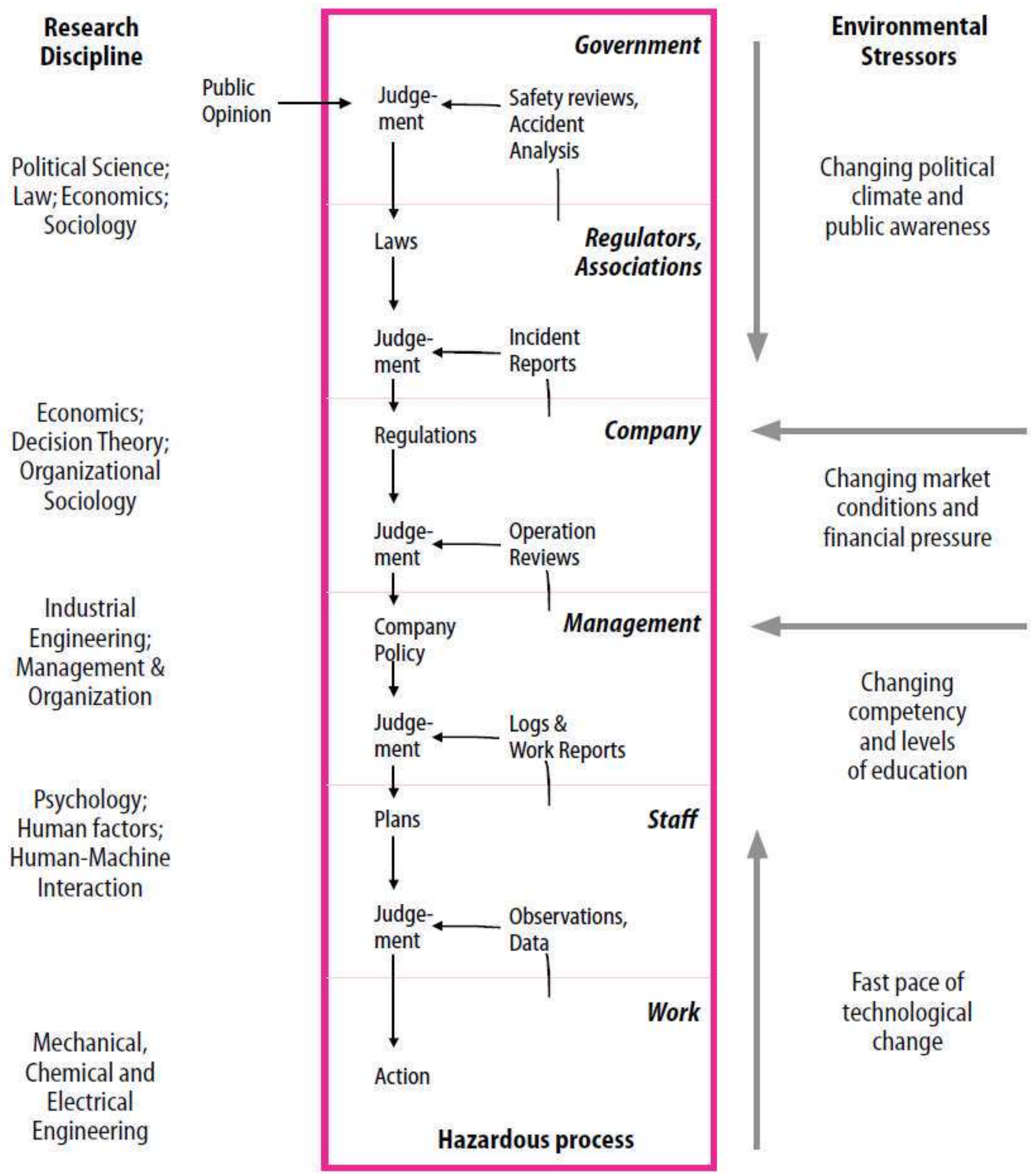


Figure 2.14: The sociotechnical system involved in risk management [Rasmussen & Svedung, 2000]

The purpose of Figure 2.14 is to show that *many levels of politicians, managers, safety officers, and work planners are involved in the control of safety by means of laws, rules, and instructions that are verbal means for the ultimate control of some hazardous, physical process. They seek to motivate workers and operators, to educate them, to guide them, or to constrain their behavior by rules*. [Rasmussen & Svedung, 2000]

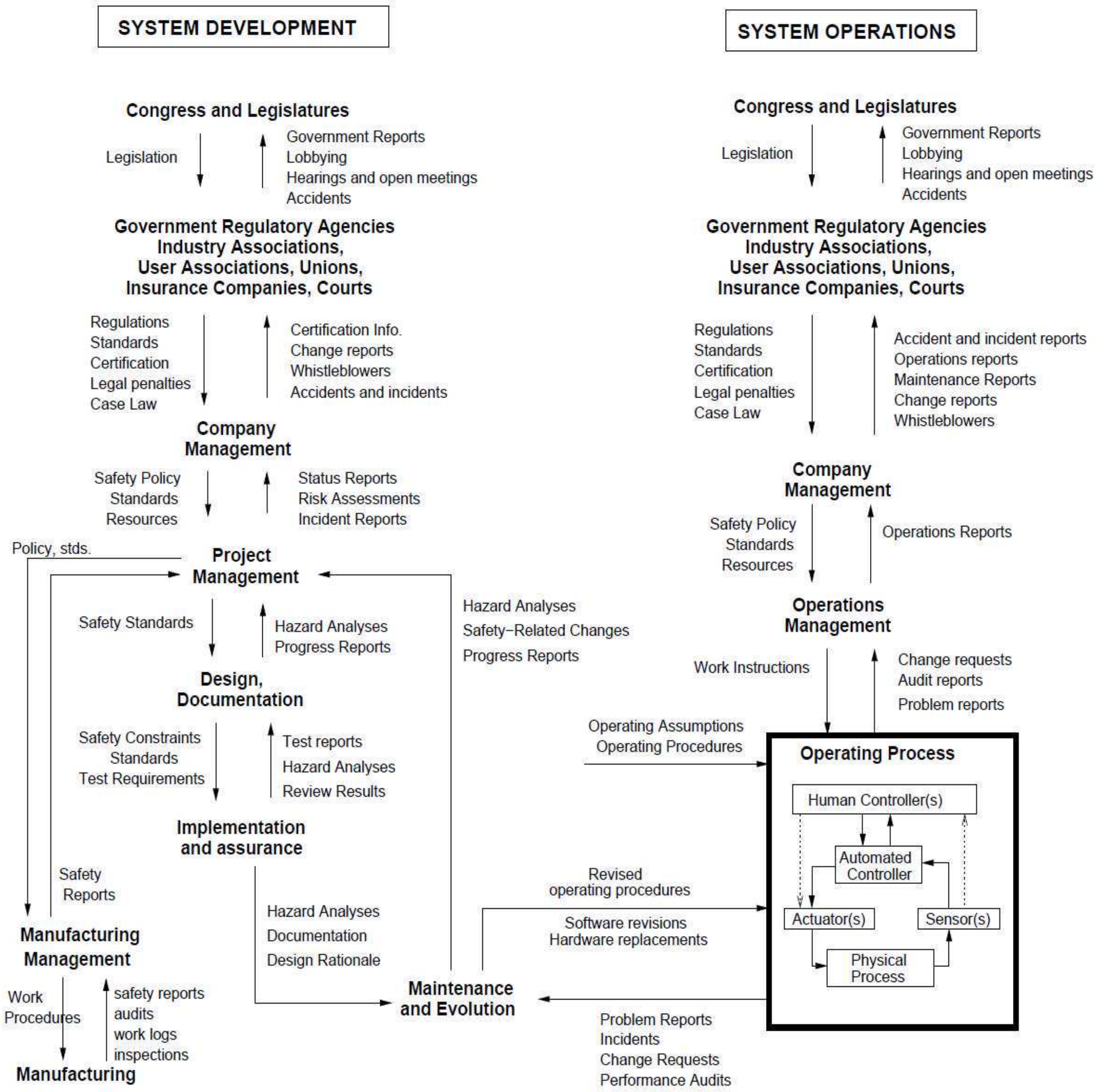


Figure 2.15: Model of sociotechnical system control [Leveson, 2009]

Figure 2.15 shows the hierarchical control structure of a system in two phases of development and operations. Documents, procedures and policies exchanged between different levels of the structure are demonstrated on the arrows.

Process models are the third significant notion in STAMP. Leveson remarks that *any automated or human control needs a model of the process being controlled to control it effectively*. Process models must include the *relationships among the system variables*, *the current state*, and *the ways the process can change state*. [Leveson, 2009]

She believes that in order to understand why accidents happen in a system and to prevent losses in future, we first need to review the control actions already available in the system. These control actions could be translated as safety constraints. Then we should review why and how inadequate control actions will lead the system to a hazardous state.

STAMP model could be applied either for analyzing accidents which have already happened or for evaluating the safety in a system, where an accident has not occurred yet.

Control system engineering emerged in 1930s, when engineers began building automatic control systems by using the techniques of electronics [Powers, 1990]. Leveson schematizes a standard control loop as following:

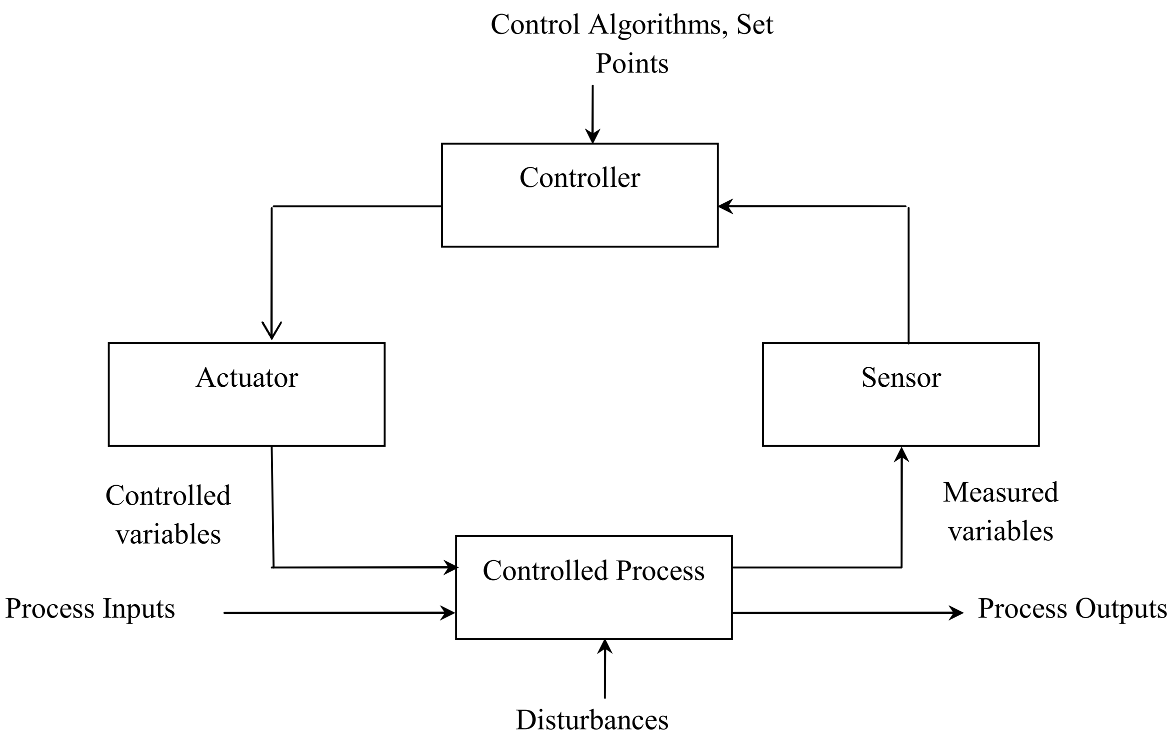


Figure 2.16: A standard control loop [Leveson, 2009]

To control a process, the controller must have four conditions:

1. Having a goal
2. Be able to affect the system
3. Be or contain a model of the system
4. Be able to observe the system

The controller observes the system by sensors, which obtains the measured variables of the system. The output of the controller affects the system by providing controlled variables through actuators. The purpose is to maintain the set point, which is the goal of the controller [Leveson, 2009].

In the field of our study, the process under control is the progress of CTSC project in a sustainable manner. The actors or stakeholders of CTSC technology are the controllers. This idea will be explained in Chapter 3.

In her new book, Leveson clearly explains the steps of applying STAMP model to analyze accidents [Leveson, 2009]:

- First of all, we should find out the events leading to the loss. It means that we simply list all the chain of events contributing in the occurrence of that accident.
- Secondly, the hazards and system boundaries should be identified.
- The next step is to find out the system safety constraints and system requirements regarding each hazard.
- Then, we should form the hierarchical structure of safety control for the system. The roles and responsibilities of each actor (controller) should be clearly defined in this structure.
- After that, the losses of physical system level should be analyzed. Four principal categories of information are required in this analysis including: safety requirements and constraints, existing controls, failures and inadequate controls, and the context.
- The sixth step is to analyze the hierarchical levels of safety control structure. In this stage, we need to collect four groups of information for each actor: safety-related responsibilities, context, unsafe decisions and control actions, and process model flaws.
- In the next step, the coordination and communication between actors (controllers) will be studied.
- Subsequently, we should study the dynamics (changes over time) relating to the loss.
- The final step is to offer recommendations to prevent similar accidents in future.

By now, this approach has been made in application for several examples. One of these examples which could be helpful to better understand the steps of an accident analysis by STAMP model, is an accident at a chemical plant called Citichem. This accident happened in Oakbridge, US, as a result of a chemical reaction between a chemical called K34 and water, entered to K34 storage tank via raining. The reaction leads to the release of a toxic gas, Tetra Chloric Cyanide (TCC) which is flammable, corrosive and volatile. 400 people were killed in this accident. Application of STAMP for analyzing this accident is presented in the subsequent paragraphs [Leveson, 2009]:

- The first step is to list the chain of events leading to the disaster.
- At the second stage, two systems are identified in Citichem, the chemical company and Oakbridge community, which is responsible to protect public health (refer to Figure 2.17 for a schematic view of these systems).

  The major components of each system and their interactions as well as the boundaries of systems are identified. And then the hazards associated with each system are found out. In this case, release of toxic chemicals and exposure of the public to toxic chemicals are the related hazards for the chemical plant and the public health structure, respectively.
- The third step is to develop the safety control structure for these two systems. To determine the components of each structure, safety-related requirements are firstly listed for each system (chemical plant and the community).
- Subsequently, the analysis starts with the plant physical safety controls. As explained before, in this part we should define safety requirements, safety controls which have existed, inadequate controls concerning physical plant and associated contextual facts.

At each stage of the analysis, recommendations can be provided to avoid inadequate safety controls.

- The analysis continues with structuring the hierarchical levels of safety control.

  Leveson has put some examples of these structures for several actors (controllers) such as maintenance worker, maintenance manager, operations manager, plant manager, corporate management, Oakbridge emergency response system, Oakbridge government and local residents. In each box, related to each actor (controller), his safety related responsibilities, the actual context in which he works or lives, his unsafe decisions and control actions and finally his process model defects (flaws) are listed.

  At the end of this part, recommendations could be provided based on the analysis.

- After analyzing the components (controllers) separately, it is essential to study the coordination and communication process among the controllers (in both directions, i.e. from the upper level to the lower one and vice versa).
- Afterwards, the changes in the system which has been directed to the accident are studied over time. In this stage, dynamic modeling could be applied in order to better understand the behavior of the system over time.

  The goal of STAMP analysis here is to specify how to *change or re-engineer the entire safety-control structure in the most cost-effective and practical way to prevent similar accident processes in the future*.
- Consequently, the final step of STAMP is to offer recommendations in order to achieve the just-mentioned goal of STAMP analysis.

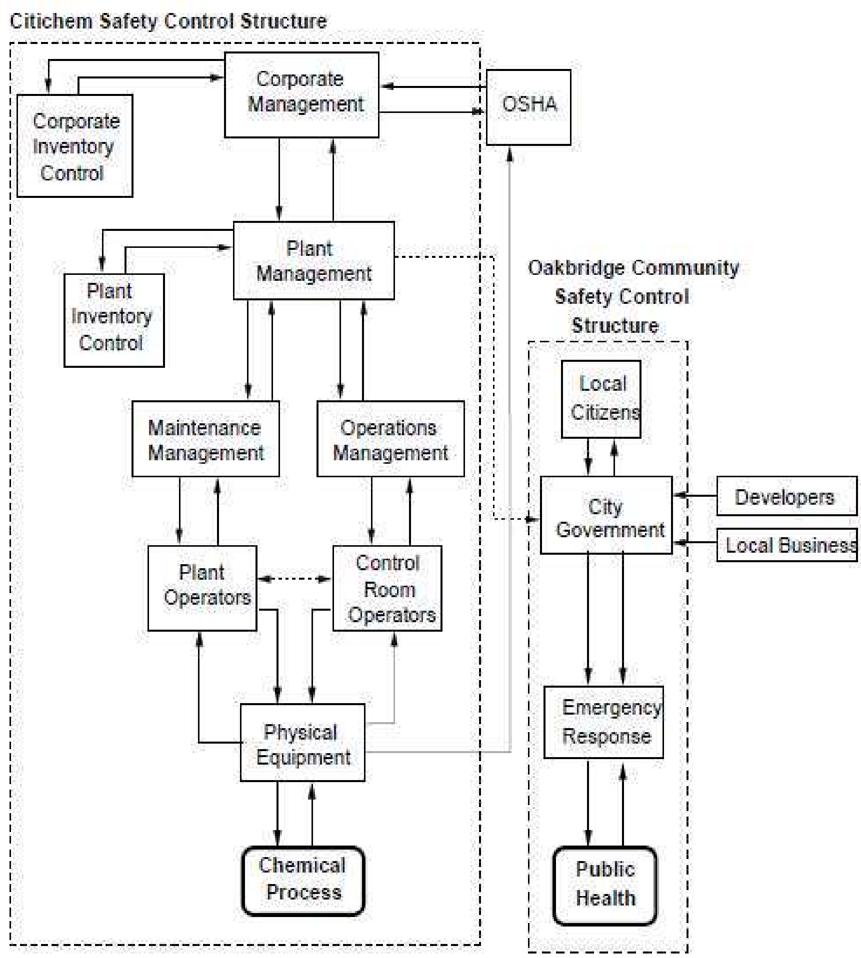


Figure 2.17: Example of a control structure relevant to an accident analysis (Citichem) [Leveson, 2009]

A systems-theoretic hazard analysis method is also developed by Leveson. This method, called STPA (Systems-Theoretic Process Analysis), is applied for the assessment of safety in a system, when an accident has not happened yet.

The obvious difference between this case and the case when we analyze an accident by STAMP is that in the former we cannot definitely identify the inadequate control actions. Alternatively, we could analyze the "potential" inadequate or insufficient safety constraints.

The steps of STPA analysis could be summarized as following [Pereira *et al.*, 2006]:

1. Review the hazards and ensure that safety constraints are in place
2. Model the hierarchical structure of safety control in the system
3. Identify potentially inadequate control actions
4. Determine how potentially inadequate control actions could lead to a hazardous situation

Leveson (2009) believes that STPA *can be used at any stage of the system life cycle*. She summarizes STPA process in two main steps:

1. Identifying potentially hazardous control actions

There are four possibilities for a control action to be hazardous:

- *A control action required for safety is not provided or is not followed.*
- *An unsafe control action is provided that leads to a hazard.*
- *A potentially safe control action is provided too late, too early or out of sequence.*
- *A safe control action is stopped too soon (for a continuous or non-discrete control action) or applied too long.*

2. Determining how unsafe control actions could occur

In this step, causal scenarios are firstly created. Afterwards, the degradation of controls over time is analyzed. To identify the causal scenarios, causal factors should be defined for each component of the control loop (controlled process, sensor, controller and actuator, as shown in Figure 2.16). The latest step of STPA is to analyze how controls could degrade over time and to consider protection barriers for the degradations. Corrosion is one of the examples, for which we have different protections, such as selecting suitable materials or regular performance audits.

A methodology is proposed for modeling the feedback network of CTSC project risks based on STAMP/STPA and system dynamics qualitative modeling. The methodology will be introduced and discussed in subsequent chapters.

Summary, Chapter 2

Chapter 2 deals with the concepts of systems theory, system dynamics and STAMP (Systems-Theoretic Accident Model and Processes). Feedback, Feedback loop, Causal graph and Delay were introduced as significant notions of system dynamics, which are essential to go on to the next chapters. □Endogenous point of view□was presented as a foundation of system dynamics, which provides endogenous explanations for all phenomena. A section was devoted to the application fields of system dynamics. Management, economics, business and environmental sciences are some of the most cited system dynamics application fields. Safety and risk management is a domain in which system dynamics has been recently employed. Examples were presented on system dynamics application in risk management. A focus was made on STAMP, developed by Nancy Leveson at MIT (Massachusetts Institute of Technology), as a systemic approach of risk and accident analysis.

A main question about CTSC at the present time is whether the technology will be developed progressively up to commercial scales. The question was reformulated in a systems thinking framework to study how dynamics of risks can affect dynamics of CTSC projects, and how interconnections of stakeholders and associated risks can result in the success or failure of a CTSC project. Current dynamics of CTSC were reviewed for the purpose of formulating this question.

Evolution of risk / safety management approaches was studied to underline the importance of systemic views in this field. STAMP major concepts, including safety constraint, hierarchical control structure and process model, were presented in order to understand how STAMP can contribute to study the risks of CTSC projects.

Résumé (French Summary of Chapter 2)

Le chapitre 2 présente les concepts de la théorie des systèmes, de la dynamique des systèmes et du modèle d’accident systémique STAMP (Systems-Theoretic Accident Model and Processes). La rétroaction, la boucle de rétroaction, le graphe causal, et le retard ont été introduits car il s’agit des notions les plus importantes de la dynamique des systèmes, celles essentielles pour poursuivre les prochains chapitres. Le « point de vue endogène » représente la base de la dynamique des systèmes et il fournit des explications endogènes pour tous les phénomènes pris en compte. Une section a été consacrée aux domaines d'application de la dynamique des systèmes. La gestion, l'économie, le business et les sciences de l'environnement sont les domaines les plus cités pour l’application de la dynamique des systèmes. La gestion de la sécurité et des risques est un champ dans lequel la dynamique des systèmes a été récemment employée. Des exemples ont été présentés sur l’application de la dynamique des systèmes dans le domaine de la gestion des risques. L'accent a été mis sur l’approche STAMP qui a été développée par Nancy Leveson au MIT (Massachusetts Institute of Technology), en tant qu’approche systémique d’analyse des risques et des accidents.

Actuellement, la principale question est de savoir si le CTSC pourra être développé progressivement jusqu’à une échelle industrielle. La question a été reformulée dans le cadre de la pensée systémique pour étudier comment la dynamique des risques pourrait affecter la dynamique des projets de CTSC, et comment les interconnexions des parties prenantes et des risques associés peuvent entraîner le succès ou l'échec d'un projet de CTSC. Cette question repose sur l’hypothèse que ce sont les interactions entre les différents éléments du système sociotechnique de CTSC qui peuvent conduire à l’émergence de situations à risques pour ces projets. Dans ce cadre, les dynamiques actuelles du CTSC ont été analysées dans le but de formuler cette question.

L’évolution des approches de gestion des risques et de la sécurité a été étudiée pour souligner l'importance d’une méthodologie systémique dans ce domaine. Les concepts majeurs de STAMP, y compris la contrainte de sécurité, la structure hiérarchique de contrôle et le modèle de processus, ont été présentés pour analyser la contribution possible de STAMP au management des risques des projets de CTSC.

Chapter 3: Proposed Systemic Methodology for Risk Management of CTSC projects

A methodology is proposed in this chapter to understand and analyze how risks could lead to success or failure of a CTSC project (risks have been previously presented in section 1.4.2.4). The objective is to model and study the safety control structure involved in a CTSC project. The methodology is based on the concepts of system dynamics and the systemic approach developed by Nancy Leveson at MIT, introduced in Chapter 2.

In this thesis, Safety is defined as the *absence of losses due to an undesired event (usually an accident)* [Leveson, 1995, p.181]. Losses in this definition include *human losses, mission or goal losses, equipment or material losses and environmental losses* [Dulac, 2007, p.31]. In this approach, *Safety is viewed as a dynamic control problem* [Leveson, 2004b, p.14].

The focus of the current thesis is on the mission or goal losses. Other kinds of failures could affect mission losses. The mission studied in this thesis is the success of a CTSC project.

In the present chapter, the methodology is firstly presented. The main risks of CTSC projects are reviewed and modeled subsequently. The application of the methodology for modeling different case studies is discussed in chapter 4.

CTSC is an emerging technology. Therefore, there is not a great amount of publicly available information on CTSC [CCP, 2007], and even less on its organizational structure. In addition, most of available information on CTSC projects success or failure are extremely sensitive. Due to the confidentiality issues, there are not many publications on this subject. However, the methodology is tested on this subject because it allows learning more about the complexity of CTSC projects risks. The required data are gathered from the available literature and project documents as well as discussions with the experts of domain.

3.1 Methodology

In Chapter 1, we introduced different categories of risk involved in CTSC projects. As explained, a list of major CTSC project risks have been identified, categorized and analyzed.

In this section, the process of modeling CTSC projects is presented.

3.1.1 Overview of the proposed methodology

The following algorithm (Figure 3.1) summarizes the steps of what was carried out in order to study safety control structure of CTSC projects. The five first steps are explained in the current chapter. The final step will be discussed in chapter 4. The purpose is to analyze the factors which make a CTSC project successful and the risks that prevent the project development.

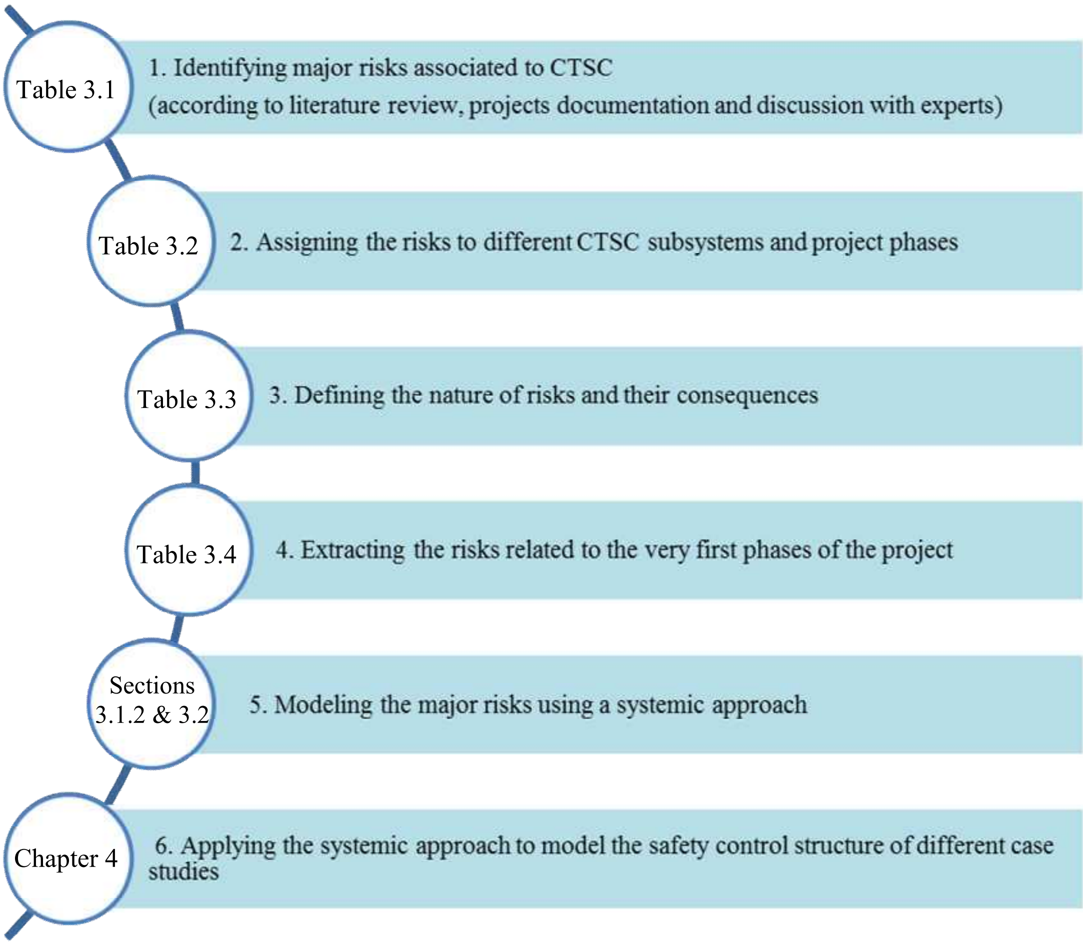


Figure 3.1: Proposed methodology steps

A list of thirty nine major risks are identified after reviewing several references [GCCSI, 2009a; GCCSI, 2011a; Longannet, 2011; Feenstra *et al.* 2010; Kerlero de Rosbo, 2009; CCP, 2007; Lacq Project, 2012]. The list is available in Table 3.1. The risks presented in this table are defined based on the project management definition of risk (*uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives*) [PMBOK, 2008].

Table 3.1: Overview of risks affecting CTSC project progress

Overview of risks affecting CTSC project progress			
1	Project permits not obtained	21	BLEVE
2	Technology scale-up	22	Lack of financial resources
3	Public Opposition	23	Lack of political support
4	Lack of knowledge/qualified resources for operating the unit	24	Phase change & material problems
5	Corrosion	25	High cost of project
6	Using the existing facilities (specially pipelines)	26	Lower Capture efficiency due to the upstream plant flexible operation
7	CO_2 out of specification	27	CO_2 leakage from compression unit
8	CO_2 plumes exceed the safe zone	28	Pipeline construction
9	Legal uncertainties	29	CO_2 leakage from pipeline
10	Safety related accident	30	Unavailability of regulations regarding different types of storage (offshore/onshore)
11	Uncertainties in stakeholders requirements/perceptions - Communication problems	31	Leakage through manmade pathways such as abandoned wells
12	Public availability of sensitive information	32	Well integrity
13	Change in policies/priorities	33	CO_2 migration
14	Financial crisis impact on financial support of CCS projects	34	Injectivity reduction over time
15	Unavailability of a monetary mechanism for CO_2	35	Uncertainties regarding the storage performance (capacity/injectivity/containment)
16	Construction field conditions	36	CO_2 leakage from storage to the surface
17	Geographical infrastructure	37	Model and data issues
18	Proximity to other industrial plants	38	Uncertainties related to storage monitoring
19	Energy consumption	39	Soil contamination
20	Maintenance and control procedures (including ESD system)		

The subsystem and project phase related to each risk are then identified (Table 3.2). Risks are listed in the first column of Table 3.2. The second column shows the related subsystem of each risk. "C", "T", "S" and "W" refer to "Capture", "Transport", "Storage" and the "Whole CTSC chain" respectively. In the other columns of Table 3.2, affected project phases from each risk are defined.

Table 3.2: Risks associated to CTSC and affected project phases

			Opportunity	Definition and planning	Engineering	Construction	Operation (Injection of CO_2)	Post-injection (Monitoring)
	Risk	**Subsystem** [1]	**Affected Project Phase**					
1	Project permits not obtained	W	x	x	x	x	x	x
2	Technology scale-up	W	x	x	x	x	x	x
3	Public Opposition	W	x	x	x	x	x	x
4	Lack of knowledge/qualified resources for operating the unit	W	x	x	x	x	x	x
5	Corrosion	W			x	x	x	x
6	Using the existing facilities (specially pipelines)	W			x	x	x	x
7	CO_2 out of specification	W					x	x
8	CO_2 plumes exceed the safe zone	W					x	x
9	Legal uncertainties	W	x	x	x	x	x	x
10	Safety related accident	W				x	x	x
11	Uncertainties in stakeholders requirements/perceptions - Communication problems	W	x	x	x	x	x	x
12	Public availability of sensitive information	W	x	x	x	x	x	x
13	Change in policies/priorities	W	x	x	x	x	x	x
14	Financial crisis impact on financial support of CCS projects	W	x	x	x	x	x	x
15	Unavailability of a monetary mechanism for CO_2	W	x	x	x	x	x	x

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage

Table 3.2: Risks associated to CTSC and affected project phases, continued

			Opportunity	**Definition and planning**	**Engineering**	**Construction**	**Operation (Injection of CO_2)**	**Post-injection (Monitoring)**
	Risk	**Subsystem** [1]	**Affected Project Phase**					
16	Construction field conditions	W				x		
17	Geographical infrastructure	W	x	x	x	x	x	x
18	Proximity to other industrial plants	W				x	x	x
19	Energy consumption	W					x	
20	Maintenance and control procedures (including ESD system)	W				x	x	x
21	BLEVE	W					x	
22	Lack of financial resources	W	x	x	x	x	x	x
23	Lack of political support	W	x	x	x	x	x	x
24	Phase change & material problems	W			x	x	x	x
25	High cost of project [2]	W	x	x	x	x	x	x
26	Lower Capture efficiency due to the upstream plant flexible operation	C					x	x
27	CO_2 leakage from compression unit	C					x	
28	Pipeline construction	T				x	x	x
29	CO_2 leakage from pipeline	T					x	

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage
2) High cost is mostly due to capture and compression high costs.

Table 3.2: Risks associated to CTSC and affected project phases, continued

			Opportunity	Definition and planning	Engineering	Construction	Operation (Injection of CO_2)	Post-injection (Monitoring)
	Risk	**Subsystem** [1]	**Affected Project Phase**					
30	Unavailability of regulations regarding different types of storage (offshore/onshore)	S	x	x	x	x	x	x
31	Leakage through manmade pathways such as abandoned wells	S					x	x
32	Well integrity	S					x	x
33	CO_2 migration	S					x	x
34	Injectivity reduction over time	S					x	
35	Uncertainties regarding the storage performance (capacity/injectivity/containment)	S	x	x	x	x	x	x
36	CO_2 leakage from storage to the surface	S					x	x
37	Model and data issues	S	x	x	x	x	x	x
38	Uncertainties related to storage monitoring	S	x	x	x	x	x	x
39	Soil contamination	S					x	x

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage

At the third step, the nature of risks and their respective consequences are defined (Table 3.3). The nature of risk and risk consequences belongs to eight categories of risk already reviewed in section 1.4.2.4. If we take □Project permits not obtained□ as an example, the risk has a legal nature and therefore, risk nature is presented by □L□ (Legal) in Table 3.3. Encountering such a risk will have consequences on the project and on global and local policies and strategies regarding CTSC. Consequently, □P□ (Project) and □P/S□(Policy/Strategy) are specified as nature of consequences of □Project permits not obtained□ The second risk is □Technology scale up□which belongs among the technical risks. Therefore risk nature is presented by □T□ Experiencing technology scale-up problems will affect the project progress. In addition, it may result not only in modifications of policies and strategies concerning CTSC technologies, but also in uncertainties about technical potential of CTSC to mitigate climate change. Hence, □P□ (Project), □P/S□ (Policy/Strategy) and □T□ (Technical) are defined as nature of consequences for □Technology scale-up□

Table 3.3 has to be read in this way.

Table 3.3: Nature of CTSC risks and their consequences

			Risk nature [2]	Nature of consequences [2]
	Risk	**Subsystem** [1]		
1	Project permits not obtained	W	L	P, P/S
2	Technology scale-up	W	T	P, P/S, T
3	Public Opposition	W	S	P, P/S, L
4	Lack of knowledge/qualified resources for operating the unit	W	T, O/H	P, P/S, HSE, O/H, T
5	Corrosion	W	T	T, P
6	Using the existing facilities (specially pipelines)	W	T	T, P
7	CO_2 out of specification	W	T	T, P, HSE
8	CO_2 plumes exceed the safe zone	W	T	P, T, HSE
9	Legal uncertainties	W	L	P, P/S, T, L
10	Safety related accident	W	T, O/H	T, O/H, P, HSE, S

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage
2) T=Technical, P=Project, S=Social, P/S=Policy/Strategy, HSE=Health, Safety, Environment, L=Legal, O/H=Organizational/Human, F/E=Financial/Economic

Table 3.3: Nature of CTSC risks and their consequences, continued

	Risk	Subsystem [1]	Risk nature [2]	Nature of consequences [2]
11	Uncertainties in stakeholders requirements/perceptions - Communication problems	W	P, P/S, HSE, O/H, T, S, L, F/E	P, P/S, HSE, O/H, T, S, L, F/E
12	Public availability of sensitive information	W	O/H, P/S	P, P/S, S, O/H
13	Change in policies/priorities	W	P/S, L	P, P/S, L
14	Financial crisis impact on financial support of CCS projects	W	F/E	P, P/S, F/E
15	Unavailability of a monetary mechanism for CO_2	W	F/E, L	P, P/S, F/E, L
16	Construction field conditions	W	T	P, T
17	Geographical infrastructure	W	T	T, P, P/S, S, HSE
18	Proximity to other industrial plants	W	T	T, P, HSE
19	Energy consumption	W	T	P, P/S, T
20	Maintenance and control procedures (including ESD system)	W	T, O/H	T, O/H, P, HSE
21	BLEVE	W	T	P, T, HSE
22	Lack of financial resources	W	F/E	P, P/S, F/E
23	Lack of political support	W	P/S	P, P/S, O/H, S, L, F/E
24	Phase change & material problems	W	T	P, T
25	High cost of project [3]	W	F/E	P, P/S, F/E
26	Lower Capture efficiency due to the upstream plant flexible operation	C	T	P, T
27	CO_2 leakage from compression unit	C	T	T, P, HSE
28	Pipeline construction	T	T	P, T
29	CO_2 leakage from pipeline	T	T	T, P, HSE
30	Unavailability of regulations regarding different types of storage (offshore/onshore)	S	L	P, P/S, L
31	Leakage through manmade pathways such as abandoned wells	S	T	P, T
32	Well integrity	S	T	P, T
33	CO_2 migration	S	T	T, P, L, S

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage
2) T=Technical, P=Project, S=Social, P/S=Policy/Strategy, HSE=Health, Safety, Environment, L=Legal, O/H=Organizational/Human, F/E=Financial/Economic
3) High cost is mostly due to capture and compression high costs.

Table 3.3: Nature of CTSC risks and their consequences, continued

	Risk	Subsystem [1]	Risk nature [2]	Nature of consequences [2]
34	Injectivity reduction over time	S	T	P, T
35	Uncertainties regarding the storage performance (capacity/injectivity/containment)	S	T	P, P/S, T
36	CO_2 leakage from storage to the surface	S	T	T, P, P/S, HSE
37	Model and data issues	S	T	P, P/S, T
38	Uncertainties related to storage monitoring	S	T	P, P/S, T, HSE, S, L
39	Soil contamination	S	T	P, T

1) W=Whole CTSC chain, C=Capture, T=Transport, S=Storage
2) T=Technical, P=Project, S=Social, P/S=Policy/Strategy, HSE=Health, Safety, Environment, L=Legal, O/H=Organizational/Human, F/E=Financial/Economic

Afterwards, major risks associated to the very first phases of the project (before engineering) are extracted. The objective is to study the causes that prevent the project progress. The major risks are presented in Table 3.4.

Table 3.4: Major risks affecting the very first phases of the project

Major risks affecting CTSC project progress (in the first phases)			
1	Project permits not obtained	10	Unavailability of a monetary mechanism for CO_2
2	Technology scale-up	11	Geographical infrastructure
3	Public Opposition	12	Lack of financial resources
4	Lack of knowledge/qualified resources for operating the unit	13	Lack of political support
5	Legal uncertainties	14	High cost of project
6	Uncertainties in stakeholders requirements/perceptions - Communication problems	15	Unavailability of regulations regarding different types of storage (offshore/onshore)
7	Public availability of sensitive information	16	Uncertainties regarding the storage performance (capacity/injectivity/containment)
8	Change in policies/priorities	17	Model and data issues
9	Financial crisis impact on financial support of CCS projects	18	Uncertainties related to storage monitoring

The four first steps of the methodology (Figure 3.1) were explained in this part. The methodology of modeling CTSC projects risk and safety control structure is presented in next sections.

3.1.2 Methodology of modeling CTSC projects safety control structure

As illustrated in Figure 3.1, major risks of CTSC projects are modeled using a systemic approach. The approach is developed based on the concepts of STAMP and system dynamics, introduced in Chapter 2. Modeling safety structure of CTSC projects is carried out within the framework of the following methodology which is composed of eight steps. The steps are schematized in Figure 3.2.

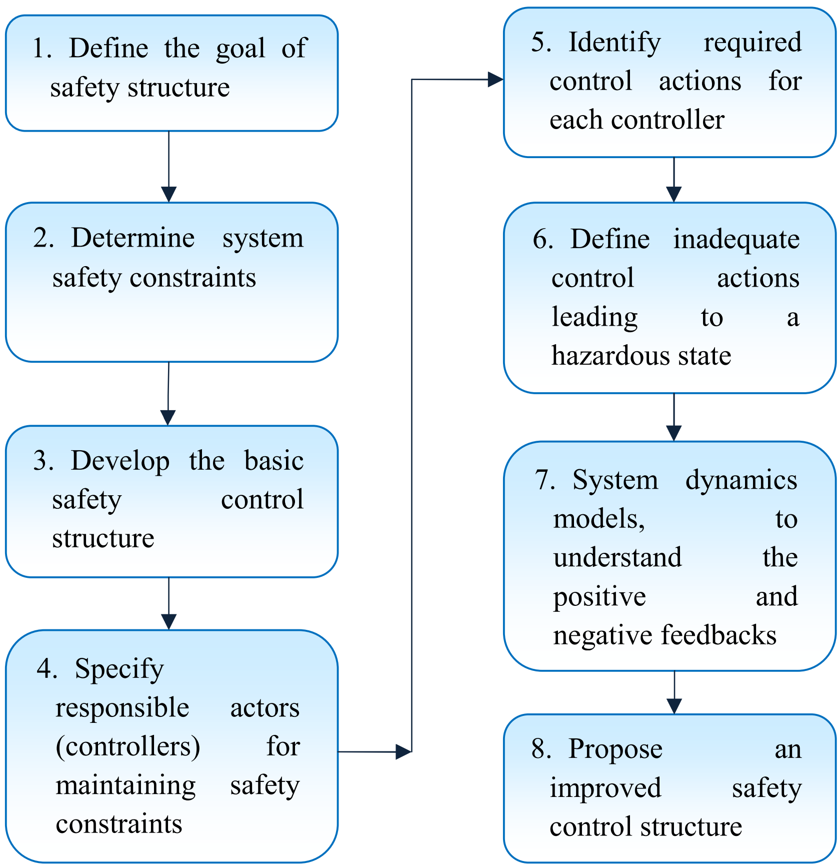


Figure 3.2: Methodology of modeling CTSC projects safety control structure

1. The first step is to define the goal of safety structure.

   A major question about CTSC at the current stage of development is why some CTSC projects are successful to progress in particular contexts, while others fail? What are the main factors that affect the project progress?

Therefore, the goal of safety structure defined in this work is to prevent the delay or cancelation of CTSC project.

This objective could be interpreted as definition and treatment of significant risks that could prevent maintaining safety constraints.

As Leveson (1995, 2004b) affirms, there are four general ways to manage risks *associated with a hazard*:

1. Eliminate the hazard from the system
2. Reduce the hazard likelihood
3. Assuring control measures when an undesired event is occurred
4. Minimize damage in case of control measures absence

2. In the second step, system safety constraints should be determined.

   With the goal defined in the first step, the following constraints could be fixed for the system:

   1st system safety constraint: The project must not be delayed or cancelled.

   2nd system safety constraint: Measures of control must be provided in case of delay or cancellation.

   In section 3.2, safety constraints will be detailed and analyzed for some major risks (defined in Table 3.4). Other relevant steps will be also discussed for each risk.

3. The basic safety control structure is developed in the third stage. A general safety control structure has been previously presented in Chapter 2, Figure 2.15.

   The structure for CTSC is context specific, depending on several factors including location, population density and historic issues [CCP, 2012]. However, the following stakeholders are present in almost all cases:

   - Project owner
   - Politicians and Policy makers (National and Local)
   - Regulators
   - External experts
   - Local population
   - NGOs
   - Media

   Each of these stakeholders is a “controller” of the system, who is responsible for maintaining specified safety constraints.

The structures will be presented and discussed when we review the case studies in chapter 4.

4. A question needs to be answered at this level. The question is who is responsible for maintaining each safety constraint?

   For the safety constraints introduced in the second step, project owner is directly responsible. In other words, project owner is the endogenous controller, while other actors are exogenous controllers, who could affect the system and decisions of the project owner.

5. At this step, required control actions for each controller should be identified. Required control actions are the tasks that should be performed in order to maintain the safety constraints. These actions are risk specific and hence will be developed later in section 3.2, when we present the constraints associated with each major risk.

6. Inadequate control actions that could lead to a hazardous state are defined in this stage. Hazardous state is a state *that violates the safety constraints* [Leveson, 2004b, p.24].

   Leveson presents four general types of inadequate control:

   1. *A required control action is not provided.*
   2. *An incorrect or unsafe control action is provided.*
   3. *A potentially correct or adequate control action is provided too late (at the wrong time).*
   4. *A correct control action is stopped too soon.*

7. System dynamics models, and especially causal graphs, are developed in this step. The purpose is to study the positive and negative feedback loops which are involved in the process of maintaining safety constraints. The models related to each major risk will be discussed in section 3.2.

8. At the final step, an improved safety control structure is proposed based on the analysis of inadequate control actions and causal graphs.

3.2 General application of the methodology: Modeling major risks affecting CTSC project progress

As discussed earlier, the goal of safety structure could be described as definition and treatment of significant risks that could prevent maintaining safety constraints. The safety constraints studied in this thesis are avoiding the projects delay or cancellation, and providing control actions if required.

Major risks associated to the CTSC whole chain were reviewed in section 3.1 and previously in Chapter 1. In this section, the specific safety constraints related to the risks are reviewed, and a number of these risks are modeled using the approach presented in section 3.1.2. Risks with different natures are selected in order to provide a more comprehensive model of risks.

3.2.1 First example: risk of not obtaining project permits

The following safety constraint could be set for this example:

Safety constraint: Required permits shall be obtained for Capture, Transport and Storage activities.

For understanding CTSC permitting procedures, a summary of significant points is provided here based on the recent report of CO_2 Capture Project on CTSC regulatory issues [CCP, 2010].

Permitting requirements are not similar in different regions. There are two *generic approaches* for regulating CO_2 storage:

- *Integrated exploration and storage licensing frameworks*. This is the case of the EU.
- *Legislative amendments associated with existing oil and gas exploration legislation*. This is the case in Australia, Canada and a part of the US.

In the EU, the CCS Directive provides the legal framework for permitting CCS activities in the Member States. However, each country is interpreting the Directive to provide a national framework.

The US and Canada are finalizing their CO_2 storage legal frameworks. In the US, regulations are provided at the Federal level. In Canada, Federal and Provincial regulations for oil and gas are the basis of CTSC regulatory framework.

The EU CCS Directive determines two major permitting frameworks for CO_2 storage:

- The first one involves with the exploration phase, *where further information is needed to determine the suitability of the proposed site for CO_2 injection*. This stage takes between 6 and 24 months to be realized.
- The second one is associated with the storage permit. *A storage permit is a written decision by a Member State Competent Authority (CA) authorizing the geological storage of CO_2 in a suitable storage site by the operator. Permitting is not required for projects that are undertaken for research, development or testing of new products and processes. The storage threshold for the determination of such projects is 100,000 tonnes of CO_2 or less per year.* Six to eight months are predicted for obtaining storage permit in the EU.

A planning process of 2-11 years is also expected. In this stage, Environmental Impact Assessment (EIA) is carried out.

The public and other third parties can influence the procedure by requesting additional information and by challenging information that has been presented. Therefore, in cases where there is public or third party opposition to the project, this stage of permitting process is particularly vulnerable to the risk of delay.

To understand the permitting procedure for Capture and Transport, the concept of "Carbon Capture Readiness" (CCR) should be reviewed. From 2009, all new combustion plants applying for operating permit in the EU have to be "CCS Ready". "CCS Ready" has been defined by different organizations such as IEA Greenhouse Gas R&D Program and GCCSI. Several points are still ambiguous in these definitions. However, the aim is to prove that CTSC technology could be introduced to the plant in the future.

In this part, we will not discuss the safety structure. Safety structures will be presented and analyzed separately in chapter 4, for each case study.

Among the general stakeholders of CTSC project, project owner is responsible for maintaining the safety constraint related to the risk of not obtaining project permits.

According to the permitting process explained earlier in this section, required control actions for the controller (project owner) are as following:

- Providing CCS Ready requirements
- Requesting exploration permit if necessary
- Carrying out the Environmental Impact Assessment (EIA) to obtain storage permit

- Communicating with the public and other stakeholders in order to avoid oppositions which may lead to project delays

Therefore, several inadequate control actions could lead to a hazardous state, where safety constraints are violated. If we take Carrying out the Environmental Impact Assessment (EIA) to obtain storage permit as an example, the process presented by ERM (Environmental Resources Management) on EIA application is as follows:

- *Upon developer s request, the competent authority sets out the EIA information to be provided by the developer.*
- *The environmental authorities must be informed and consulted throughout the process.*
- *The public must be informed and consulted. A common practice is a 30 day public consultation after the EIA report is publicly published.*
- *If the EIA report is substantially changed as the result of the consultations, it has to be put for another public consultation and so on, until there are no significant changes needed.*
- *The competent authority decides on the acceptability of the report and the project, taken into consideration the results of consultations.*
- *The public is informed of the decision afterwards and can challenge the decision before the courts.* [CCP, 2010, p.30]

A number of inadequate control actions could be named by focusing on the details of the EIA application process. Hereafter, examples of such inadequate control actions are provided:

1. Environmental Impact Assessment is not provided.
2. Environmental authorities or public are not informed and consulted throughout the process.
3. Potential required changes of EIA report as the result of consultations are implemented too late.
4. Communication with the stakeholders is stopped too soon. (Therefore, all stakeholders feedbacks could not be taken into consideration in the EIA report).

Positive and negative feedbacks having an impact on the risk of not obtaining the required permits are shown in the following figure:

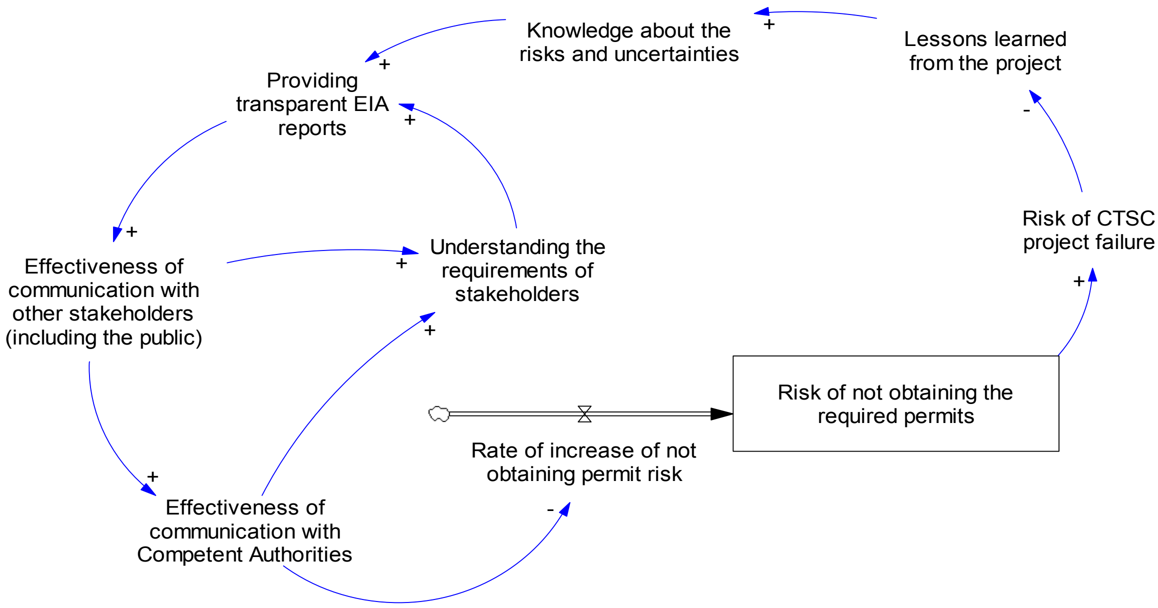


Figure 3.3: Feedback network affecting the risk of not obtaining the required permits

Risk of not obtaining the required permits is considered as a stock variable, since it is an accumulation in the system which we need to control. Rate of increase of the risk is a flow variable. Various control or auxiliary variables could lead to the modification of our flow variable. Effectiveness of communication with Competent Authorities reduces the risk of not obtaining the permits (negative feedback). Such effectiveness is a result of having effective communication with other stakeholders (including the public). A positive feedback loop is generated when the feedbacks from communication with stakeholders provide us with their requirements. As a result, more transparent EIA reports will be prepared, and the communication effectiveness will be increased consequently. Providing transparent EIA reports also requires knowledge on the risks and uncertainties. The knowledge could be improved by getting and analyzing lessons learned from the project. More lessons learned could be obtained if projects do not fail.

A summary of analyzing the first example with the systemic approach is provided in the following table:

Table 3.5: Summary of first example, risk of not obtaining the required permits

Risk: Not obtaining the required permits
Safety Constraint:
Required permits shall be obtained for Capture, Transport and Storage activities.
Who is responsible for maintaining the safety constraint?
Project owner
Required Control Actions:
- Providing CCS Ready requirements - Requesting exploration permit if necessary - Carrying out the Environmental Impact Assessment (EIA) to obtain storage permit - Communicating with the public and other stakeholders in order to avoid oppositions which may lead to project delays
(Examples of) Inadequate Control Actions leading to a hazardous state:
- Environmental Impact Assessment is not provided. - Environmental authorities or public are not informed and consulted throughout the process. - Potential required changes of EIA report as the result of consultations are implemented too late. - Communication with the stakeholders is stopped too soon. (Therefore, all stakeholders feedbacks could not be taken into consideration in the EIA report).

3.2.2 Second example: risk of technology scale-up problems

As Herzog argues, in order to realize the objective of cutting greenhouse gas emissions by 2050, we will need to capture and store gigatonnes of CO_2 every year. He mentions the following challenges for CTSC scale-up [Herzog, 2009]:

- Cost
- Infrastructure
- Subsurface Uncertainty (Capacity & Long-term Integrity)
- Regulatory Framework
- Long-term Liability
- Public Acceptance

The safety constraint for the current example is as follows:

Safety constraint: Measures must be put in place to avoid the risk of delay or cancellation due to technology scale-up issues.

According to Herzog's point of view, CTSC technology scale-up is a complex issue that depends on various factors. Hence, several stakeholders are involved as the controllers of such a complex subject.

Project owner and Competent Authorities could be considered as endogenous controllers, while Regulators, Local population and others are the exogenous controllers, which have impacts on the decisions of endogenous actors. In this report, we focus on the endogenous ones.

Required control actions for each controller are as coming next:

For project owner:

- Providing the required elements to minimize the uncertainties associated to subsurface and storage long term liability
- Ensuring the public acceptance of the project development
- Providing the necessary infrastructure
- Providing technologies with optimized acceptable costs

And for Competent Authorities:

- Providing regulatory frameworks for CTSC activities

Once again, a number of inadequate control actions could be analyzed for each controller. Examples of inadequate control actions of project owner on the subject of "providing technologies with optimized acceptable costs" are as following:

1. Acceptable costs are not proposed for CTSC technologies.
2. Best available costs are proposed by the developers, but not accepted by the authorities because of uncertainties/ambiguities of acceptable costs range.
3. Economically acceptable options are made available too late.
4. Research and Developments are not continued to find more economic technological possibilities (as soon as an option is accepted by the authorities) (There is a risk of changing range of acceptable costs over time).

The feedbacks involved in controlling the rate of increase of technology scale-up problems are illustrated in the following causal graph:

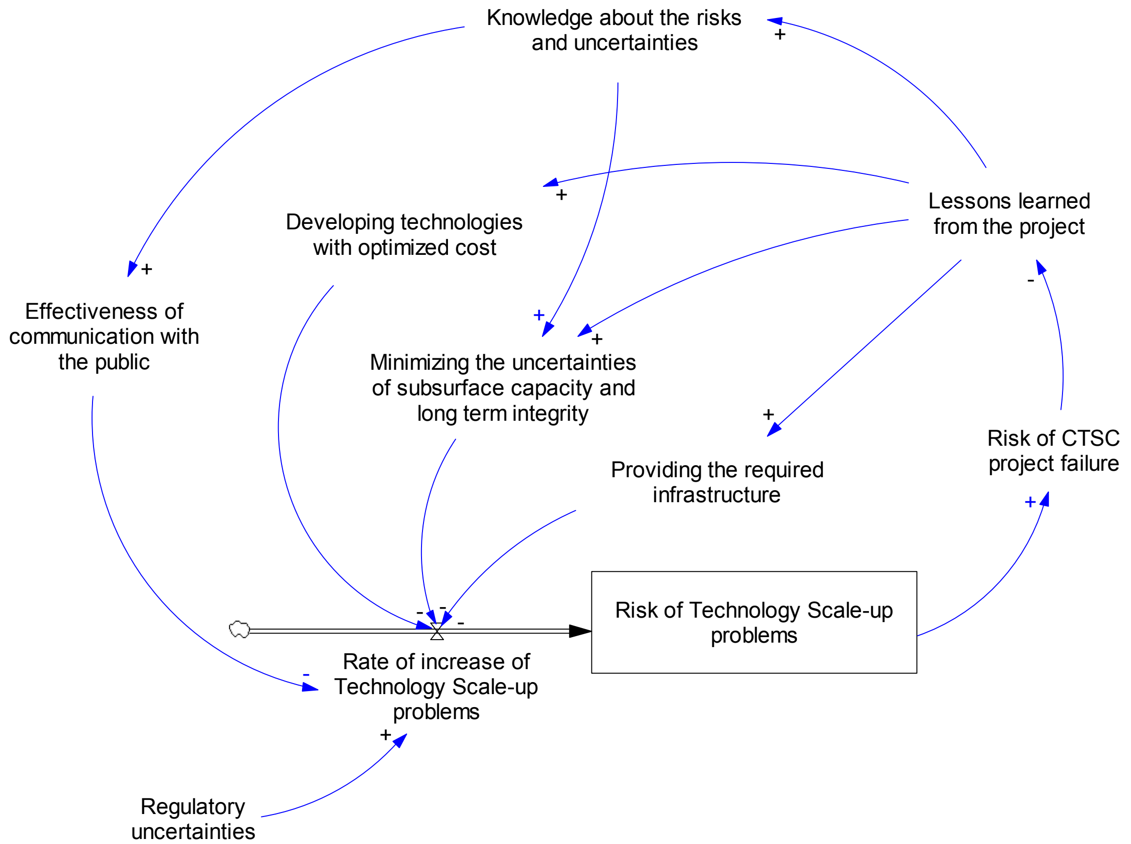


Figure 3.4: Feedback network affecting the risk of technology scale-up problems

Risk of technology scale-up issues and the rate of risk increase are again presented as stock and flow variables respectively. Challenges of scale-up, introduced at the beginning of this section, are the control variables affecting the rate of increase of technology scale-up problems. The challenges are represented as Providing the required infrastructure, Minimizing the uncertainties of subsurface capacity and long term integrity, Developing technologies with optimized cost, Effectiveness of communication with the public and Regulatory uncertainties.

Some variables such as risk of project failure, lessons learned and knowledge about the risks and uncertainties which are involved in the feedback network of the current example were also included in the previous model (Figure 3.3).

This example makes us recall that the risks are interdependent. Therefore, the safety constraints are strictly interrelated in some cases. The models covering risk interconnections will be presented in section 3.2.6.

A summary of analyzing the second example with the systemic approach is provided in the following table:

Table 3.6: Summary of second example, risk of technology scale-up problems

Risk: Technology scale-up problems
Safety Constraint:
Measures must be put in place to avoid the risk of delay or cancellation due to technology scale-up issues.
Who is responsible for maintaining the safety constraint?
Project owner & Competent Authorities
Required Control Actions:
For project owner: - Providing the required elements to minimize the uncertainties associated to subsurface and storage long term liability - Ensuring the public acceptance of the project development - Providing the necessary infrastructure - Providing technologies with optimized acceptable costs And for Competent Authorities: - Providing regulatory frameworks for CTSC activities
(Examples of) Inadequate Control Actions leading to a hazardous state:
- Acceptable costs are not proposed for CTSC technologies. - Best available costs are proposed by the developers, but not accepted by the authorities because of uncertainties/ambiguities of acceptable costs range. - Economically acceptable options are made available too late. - Research and Developments are not continued to find more economic technological possibilities (as soon as an option is accepted by the authorities) (There is a risk of changing range of acceptable costs over time).

3.2.3 Third example: risk of public opposition

Poumadère *et al.* mention several points that drive CTSC public acceptance. Public perception of climate change, trust in industry and organizations in charge of project development, public participation from the very first phases of the project, history of the storage site, and socio-demographic characteristics of the local population (such as age, sex and level of higher education) are the major issues that stimulate the public to accept CTSC as a mitigation technology to deal with climate change [Poumadère *et al.*, 2011].

The safety constraints for public opposition risk are as follows:

<u>Safety constraint 1</u>: Local population agreement should be assured.

<u>Safety constraint 2</u>: In case of opposition, measures should be in place to reduce the risk of project delay or cancellation.

Project owner is responsible to ensure and provide the required supports for maintaining safety constraints.

Required control actions for project owner include:

- Direct communication with the community from the initial phases of the project
- Giving information to the public in a less complicated manner (not too technical)
- Making the public trust them by highlighting the mutual benefits from the project development (including CTSC role in Climate Change mitigation)
- Making the public trust them by sharing the uncertainties and risks

Different inadequate control actions are conceivable for each required control action. If we take □Direct communication with the community from the initial phases of the project□as an example, inadequate control actions will be as succeeding:

1. Direct communication with the stakeholders is not provided.
2. Communication with the stakeholders is performed indirectly (via media or third parties, for example).
3. Direct communication with the stakeholders is provided too late.
4. Project developers do not continue to directly communicate with the stakeholders during the life cycle of the project.

Figure 3.5 summarizes the variables involved in the control process of public opposition risk.

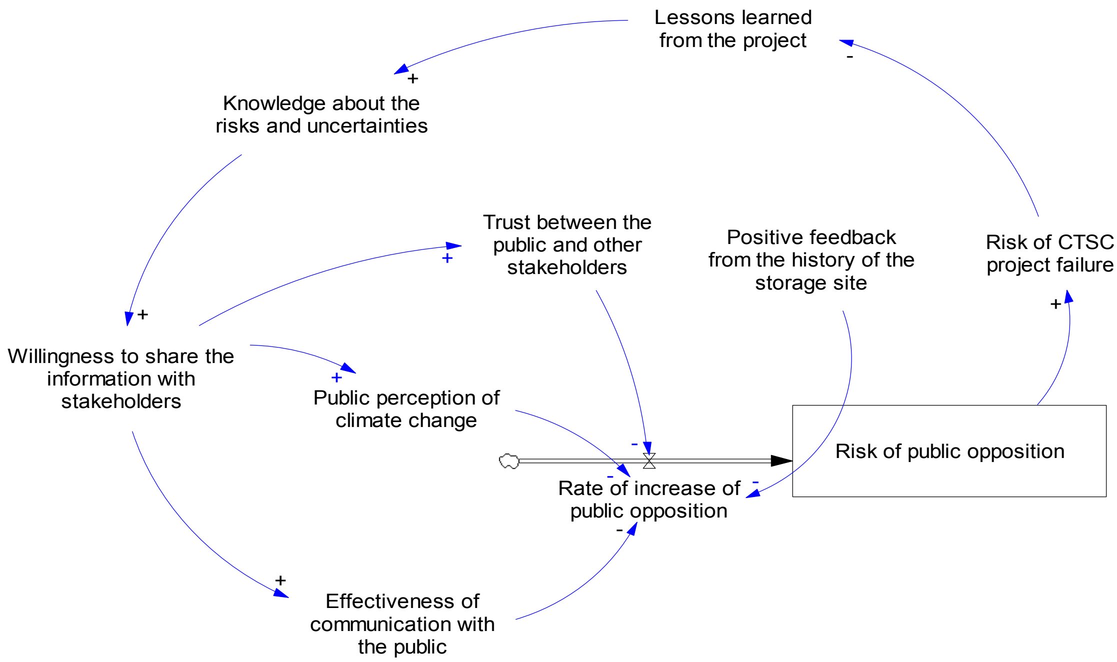


Figure 3.5: Feedback network affecting the risk of public opposition

In order to reduce the rate of public opposition risk, more effective communication has to be ascertained. Once more, improving our knowledge through the lessons learned will increase our willingness to share the information with the stakeholders and among them the local community. Sharing the information will make the public trust the project owner and other stakeholders. In addition, public perception of climate change will be improved. As previously mentioned, the history of the storage site is a significant factor for assuring public acceptance.

Analysis of public opposition example is sum up in Table 3.7.

Table 3.7: Summary of third example, risk of public opposition

Risk: Public opposition
Safety Constraints:
- Local population agreement should be assured. - In case of opposition, measures should be in place to reduce the risk of project delay or cancellation.
Who is responsible for maintaining the safety constraint?
Project owner
Required Control Actions:
- Direct communication with the community from the initial phases of the project - Giving information to the public in a less complicated manner (not too technical) - Making the public trust them by highlighting the mutual benefits from the project development (including CTSC role in Climate Change mitigation) - Making the public trust them by sharing the uncertainties and risks
(Examples of) Inadequate Control Actions leading to a hazardous state:
- Direct communication with the stakeholders is not provided. - Communication with the stakeholders is performed indirectly (via media or third parties, for example). - Direct communication with the stakeholders is provided too late. - Project developers do not continue to directly communicate with the stakeholders during the life cycle of the project.

3.2.4 Fourth example: risk of model and data issues

Koornneef *et al.* (2012) have recently reviewed major gaps and uncertainties regarding the environmental and risk assessment of CTSC activities. They argue that these uncertainties *have the potential to postpone the implementation* of CTSC. The uncertainties are listed hereunder:

Capture:

- Uncertainties concerning quantification of atmospheric emissions when a CO_2 capture process is integrated in a power plant
- Uncertainties about flows and composition of wastes and byproducts of power plants with CO_2 capture

Transport:

- Uncertainties about the rate and characteristics of CO_2 pipeline leakage
- Uncertainties related to corrosion rates of pipelines when impurities such as H_2O, SO_x, NO_x, N_2, O_2, H_2S, CO and H_2 are present.
- Uncertainties about the effects of impurities in dispersion models

Storage:

- Uncertainties regarding characteristics (amount and speed) of fluxes between subsurface compartments and possible leakage pathways
- Uncertainties concerning sealing capacity (containment), injectivity and storage capacity
- Uncertainties about monitoring of deep subsurface
- Additional uncertainties due to the post-closure phase, which is specific to CO_2 long term storage

Most of the uncertainties are linked to modeling issues. Modeling is a dynamic process which begins at the initial phase of the project. Models are continually updated and validated based on the lessons learned and the information acquired from the field.

Koornneef *et al.* (2012) mention that modeling CO_2 behavior in reservoirs has been already experienced in EOR projects. However, geochemical, geophysical and hydrodynamic interactions of CO_2 with the reservoir have not been detailed. Therefore, *the models are not calibrated yet for long term CO_2 storage*.

Dynamic evolution of uncertainties during the life cycle of CTSC project is illustrated in the following figure:

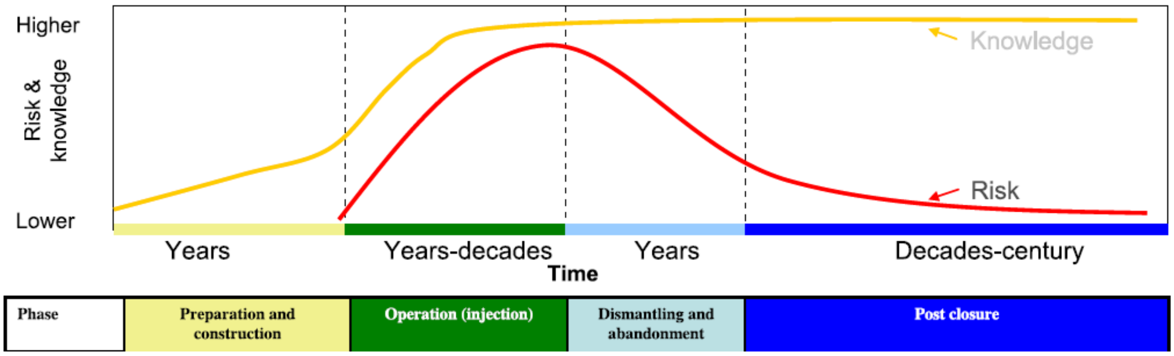


Figure 3.6: Evolution of risks and knowledge during CTSC project life cycle [Koornneef *et al.*, 2012]

Knowledge is considered as the *inverse of uncertainty* in Figure 3.6. This means that uncertainties decrease with time through the project development.

Post-closure is a phase which does not exist in a typical analogous project in oil and gas field. Therefore, additional uncertainties are generated in post-closure phase due to *data limitations*, *dynamic modeling of CO_2*, *long term subsurface interactions* and *caprock characterization*. [Koornneef et al, 2012]

Model and data issues discussed in this section refers to the overall idea of uncertainties in modeling CTSC systems, without focusing particularly on any subsystem of capture, transport or storage.

Hence, the safety constraint for model and data issues is as follows:

<u>Safety constraint</u>: Models and data should be consistent with reality.

Project owner is responsible to provide the required control actions to maintain this safety constraint.

Subsequent control actions are required for the project owner:

- Regularly updating modeling techniques and approaches based on the lessons learned and research & development
- Regularly updating models and data based on the information obtained from the field

Following inadequate control actions are conceivable:

1. Modeling techniques are not updated.
2. Updated modeling techniques are not available for the engineers.
3. Feedbacks from the lessons learned are not implemented on the models on a regular basis.

4. Research and development do not proceed to improve the modeling approaches.

Figure 3.7 summarizes the variables involved in the control process of model and data issues:

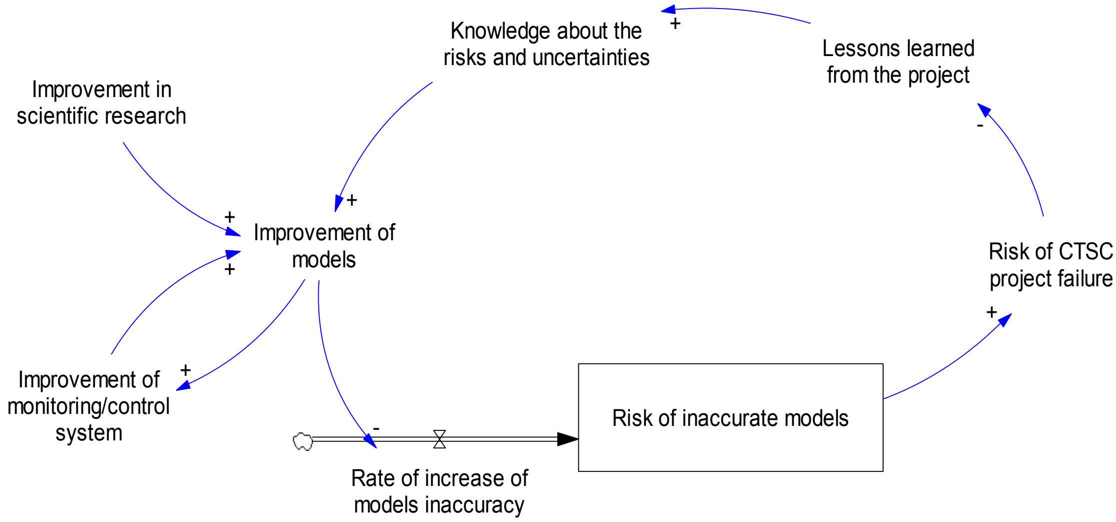


Figure 3.7: Feedback network affecting the risk of model and data issues

Risk of having inaccurate models is another stock variable, which could be decreased by improving the models. Models could be improved by feedbacks from the scientific research progress, as well as lessons learned from the field data. Amelioration of monitoring and control system generates a positive feedback loop to improve the models.

A summary of analyzing the fourth example with the systemic approach is provided in Table 3.8.

Table 3.8: Summary of fourth example, risk of model and data issues

Risk: Model and data issues
Safety Constraint:
Models and data should be consistent with reality.
Who is responsible for maintaining the safety constraint?
Project owner
Required Control Actions:
- Regularly updating modeling techniques and approaches based on the lessons learned and research & development - Regularly updating models and data based on the information obtained from the field
(Examples of) Inadequate Control Actions leading to a hazardous state:
- Modeling techniques are not updated. - Updated modeling techniques are not available for the engineers. - Feedbacks from the lessons learned are not implemented on the models on a regular basis. - Research and development do not proceed to improve the modeling approaches.

3.2.5 Fifth example: risk of financial resource shortage

Financial support is essential to have commercial scale CTSC projects. Several projects have been stopped due to financial resource problems. Longannet project in the United Kingdom is an example. The project was cancelled in October 2011, since it was not affordable, and stakeholders risk perceptions were different [Thomas *et al.*, 2012; GCCSI, 2012a]. On June 26, 2012, Peel Energy project in the UK was cancelled due to *the economic slowdown and uncertainties around public funding*. [GCCSI, 2012a]

The safety constraint for the risk of financial support shortage could be formulated as follows:

<u>Safety constraint</u>: Financial support shall be ensured for commercial scale CTSC projects.

Government and project owner are responsible to maintain the safety constraint.

Required control actions for each controller are as coming next (if we assume that CTSC project has a public financial support):

For government:

- Providing the necessary financial support for the project

And for project owner:

- Correctly estimating the required financial resource in the feasibility studies
- Allocating the received financial support for the project development

Taking into account Correctly estimate the required financial resource in the feasibility studies, following inadequate control actions are conceivable for project owner as the relevant controller:

1. Cost estimation is not performed correctly at the initial phases.
2. Effect of some parameters is not taken into account in the first cost estimations.
3. Realistic cost estimations are provided too late.
4. Feedbacks from external experts/suppliers are not completely integrated in project cost calculations.

The feedback network affecting lack of financial resource is showed in the following figure:

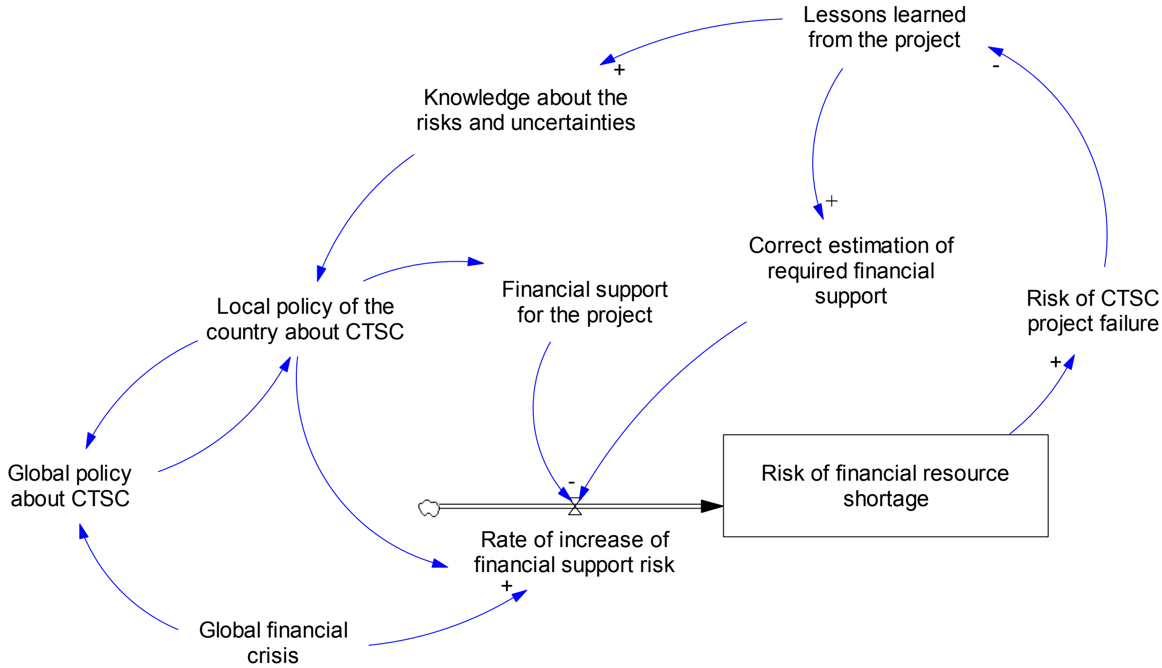


Figure 3.8: Feedback network affecting the risk of financial resource shortage

Rate of financial support risk is directly affected by local policy of each region about CTSC. Local policy and national/international policies are mutually interconnected. Lessons learned and knowledge about the risks and uncertainties will have an effect upon policies. The policies about CTSC determine whether funds will be allocated for the CTSC project. Furthermore, correct estimation of required financial support could be assured by the lessons learned from the project. As illustrated in Figure 3.8, the feedbacks of knowledge/policy, local/global policies, policy/financial support, policy/risk of financial lack and cost estimation/risk of financial lack do not have any positive or negative sign. This is due to the uncertainties about whether knowledge improvement on CTSC could lead to change the policies to more or less investment on CTSC technology. These uncertainties are formulated by Tombari as “learning curve” uncertainty. The idea is that we are not sure if learning from CTSC projects results in getting less expensive technologies. The notion of learning curve comes from Schlumberger Carbon Services, who believes that First Of A Kind (FOAK) CTSC plants will experience a “*pre-learning*” *phase, in which cost decreases will not be uniform*. It is argued that immature technologies often go through this phase which is *commonly referred to as the* “*valley of death*”. *In order to advance, the technology requires more and more funding with riskier returns* [Tombari, 2011; Soupa *et al.*, 2012]. In addition, global financial crisis has an influence on global policy about CTSC. Positiveness or negativeness of the feedback is uncertain at the moment.

Analysis of financial resource shortage risk is sum up in Table 3.9:

Table 3.9: Summary of fifth example, risk of financial resource shortage

Risk: Financial resource shortage
Safety Constraint:
Financial support shall be ensured for commercial scale CTSC projects.
Who is responsible for maintaining the safety constraint?
Government & Project owner
Required Control Actions:
For government: - Providing the necessary financial support for the project And for project owner: - Correctly estimating the required financial resource in the feasibility studies - Allocating the received financial support for the project development
(Examples of) Inadequate Control Actions leading to a hazardous state:
- Cost estimation is not performed correctly at the initial phases. - Effect of some parameters is not taken into account in the first cost estimations. - Realistic cost estimations are provided too late. - Feedbacks from external experts/suppliers are not completely integrated in project cost calculations.

3.2.6 Risk interconnections and example of a regrouped model

As discussed earlier, CTSC is a novel complex technology for which risks cannot be analyzed and managed separately. The interrelations of risks create a context which has the potential to give rise to a hazardous state. Therefore, the interconnections of risks shall be modeled and studied. Major risks affecting CTSC project development were introduced in Table 3.4. Inter-relations of the risks are illustrated in the following causal graph. The green bold feedbacks represent the risks interconnections.

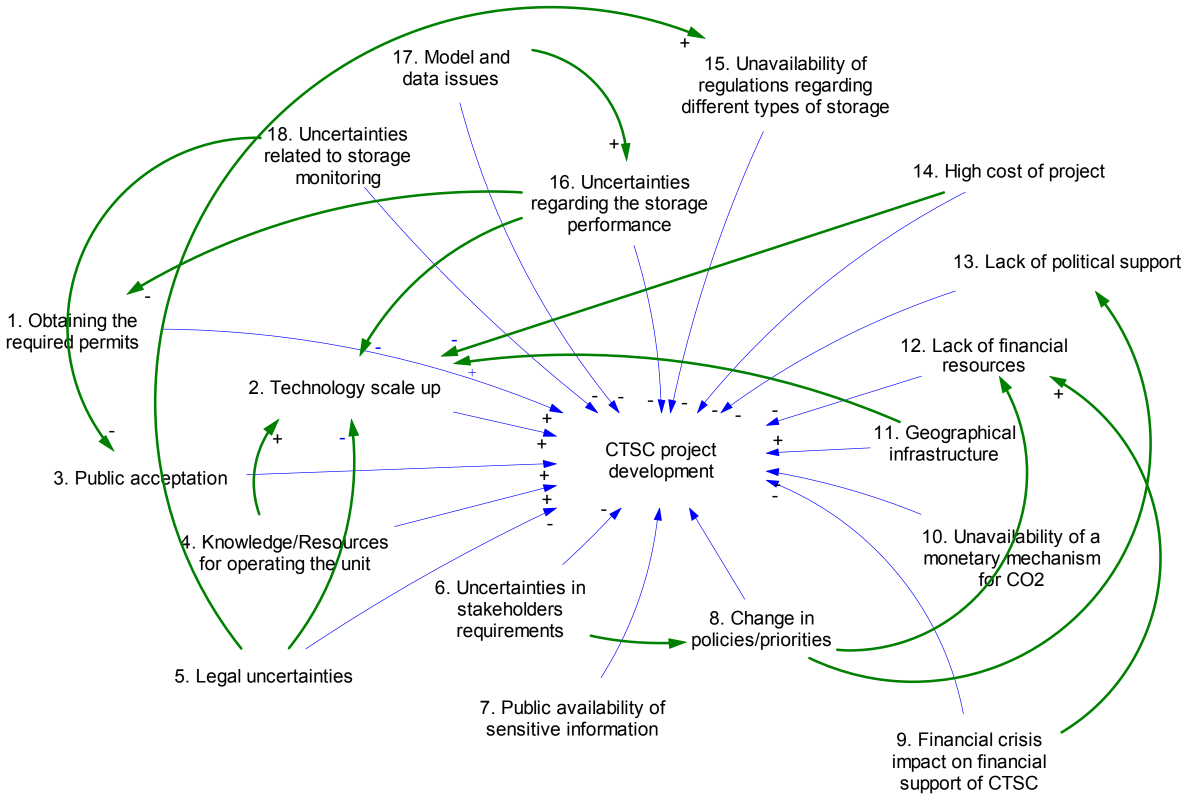


Figure 3.9: Interconnections of major risks affecting CTSC projects progress

An example of risk interconnections is "Technology scale up" which is influenced by five other risks: "Knowledge/Resources for operating the unit", "Legal uncertainties", "Geographical infrastructure", "High cost of project" and "Uncertainties regarding the storage performance". These notions have been already introduced in section 3.2.2.

Regrouping the risks explained in the previous pages (sections 3.2.1 to 3.2.5) results in the following model (Figure 3.10).

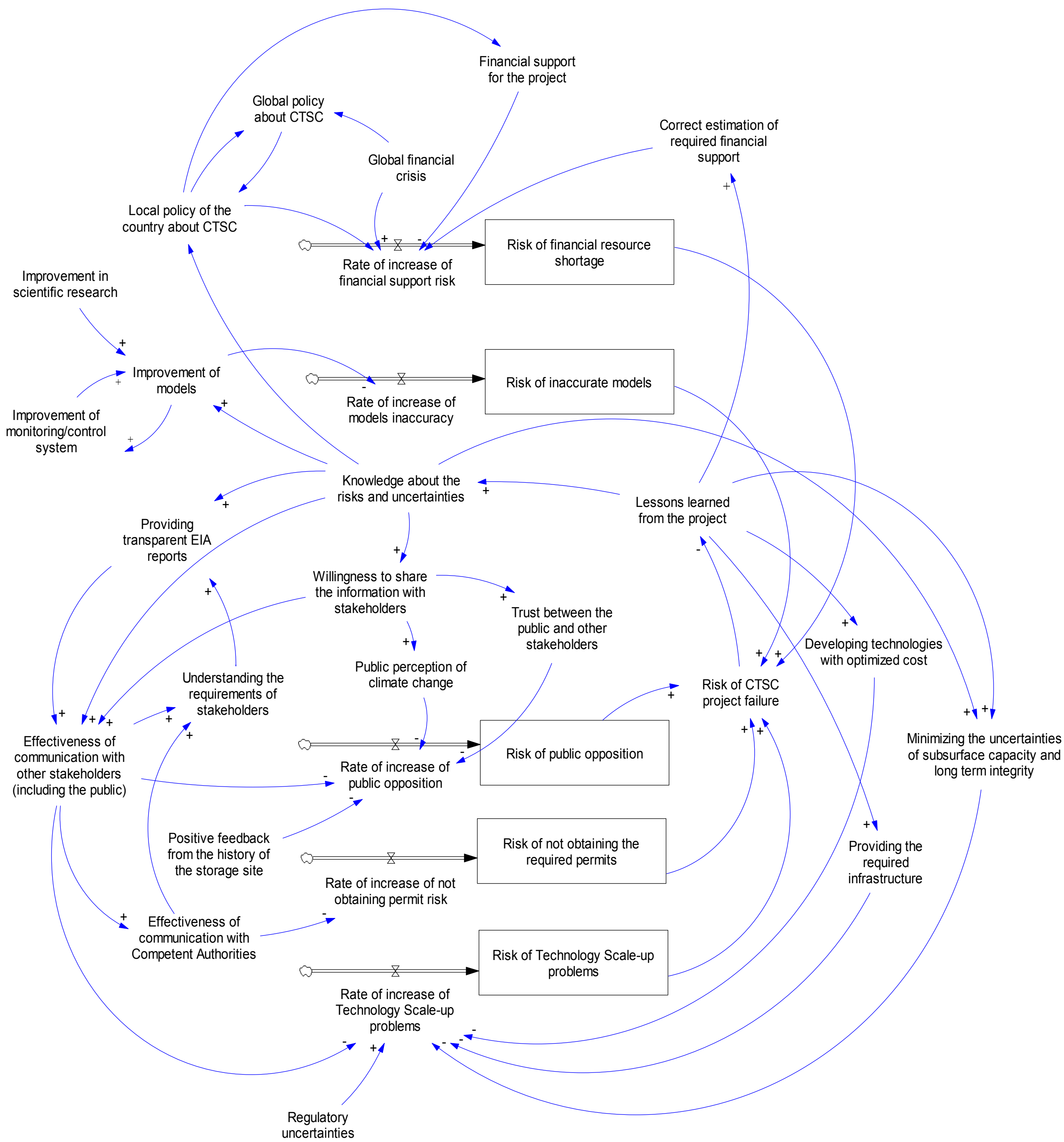


Figure 3.10: Overall feedback network of the risks presented in section 3.2

Figure 3.10 provides some potential interconnections of different types of risks and accordingly among variables of models previously presented in Figures 3.3 to 3.8. An example is shown in Figure 3.11 (marked in red) to help the reader understanding Figure 3.10.

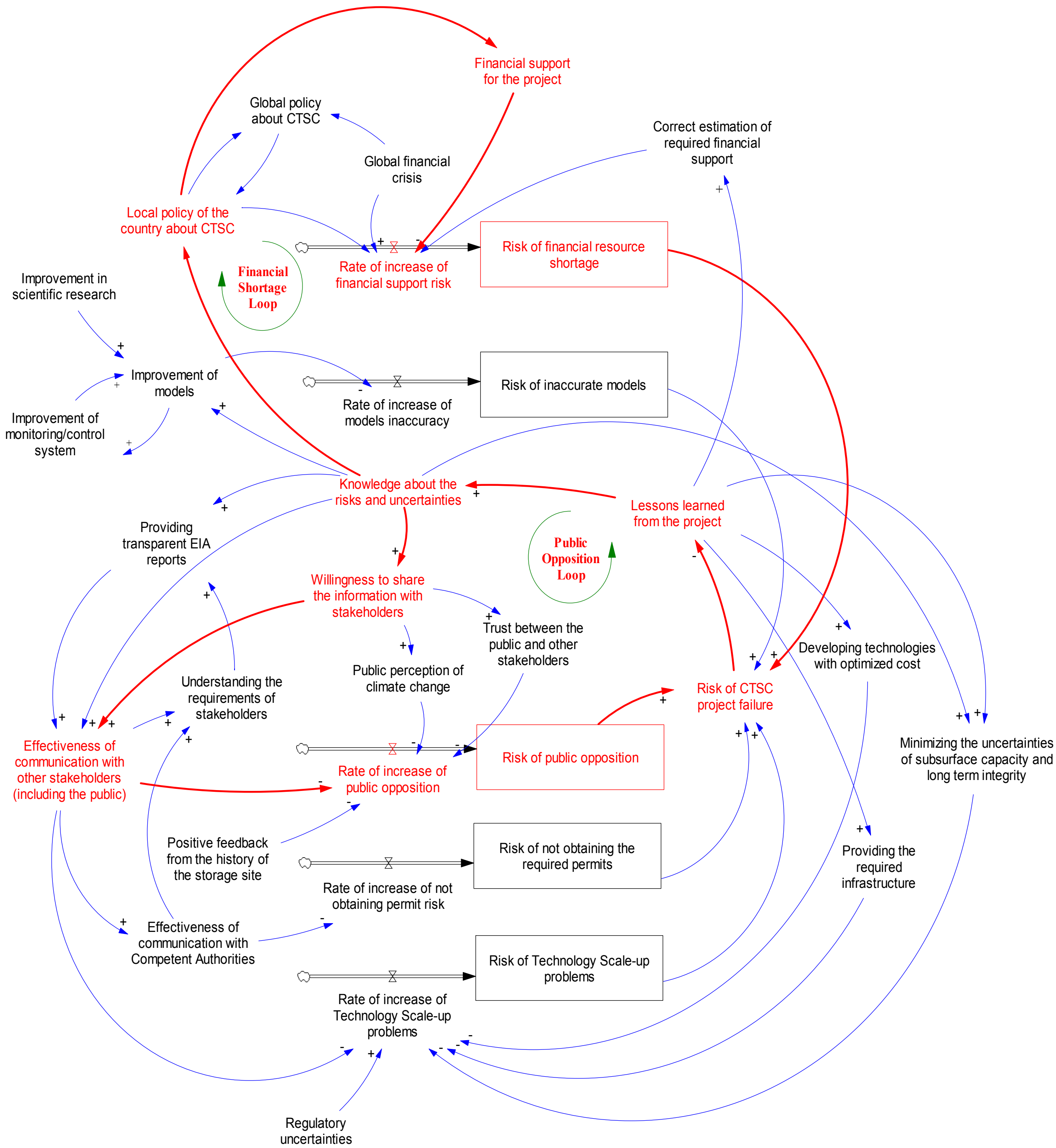


Figure 3.11: Overall feedback network of the risks, examples of loops

If we start from "Risk of public opposition", as explained in section 3.2.3, effectiveness of communication with the public could reduce the rate of increase of public opposition (negative feedback between "Effectiveness of communication with other stakeholders (including the public)" and "Rate of increase of public opposition"). Effectiveness of communication is a result of willingness to share the information, which depends on the knowledge we are gaining about the risks and uncertainties (positive feedbacks of

“Knowledge about the risks and uncertainties”, “Willingness to share the information with stakeholders” and “Effectiveness of communication with other stakeholders (including the public)”). Knowledge about the risks and uncertainties will improve by analyzing lessons learned from the project (positive feedback between “Lessons learned from the project” and “Knowledge about the risks and uncertainties”). A loop is created when the risk of public opposition leads to project failure, and therefore not obtaining lessons learned from the project (negative feedback between “Risk of CTSC project failure” and “Lessons learned from the project”). The loop is entitled “Public Opposition Loop” in Figure 3.11. Knowledge about the risks and uncertainties will also have impacts on CTSC local policy and providing funds for the project, which will obviously reduce the rate of increase of financial support risk. Risk of financial resource shortage will create another loop by affecting the risk of CTSC project failure (Financial Shortage Loop in Figure 3.11). The two presented loops are interconnected.

Interrelations of risks illustrated in Figures 3.10 and 3.11 have to be read as explained in previous paragraph by studying the feedback loops.

Some control variables of Figures 3.10 and 3.11 are in fact the stock variables with their own specific flow variables, since they are the major risks of CTSC project development. These variables are represented as auxiliary variables in order to avoid the complexity of models. “Global financial crisis”, “Understanding the requirements of stakeholders”, “Regulatory uncertainties” and “Providing the required infrastructure” are some examples of the variables that could be considered as stock variables. CTSC project failure is at the heart of the model. Major risks are the level variables which have a cumulative effect on project failure.

Modeling major risks of CTSC projects with our systemic approach was presented in this section. Safety control structures of different case studies will be presented and discussed in the next chapter. The purpose is to find the elements leading to CTSC projects success or failure in various contexts.

Summary, Chapter 3

The systemic methodology which is proposed for risk management of CTSC projects was introduced in this chapter. At the beginning, an overview of the methodology was presented. The methodology is founded on the concepts of STAMP and system dynamics. The objective is to model and analyze safety control structure involved in a CTSC project. Safety control structure is the organizational structure of stakeholders who are responsible for maintaining safety constraints. The goal of safety control structure in this work is to prevent CTSC projects delay or failure. This goal was rephrased as definition and treatment of significant risks that could avoid maintaining safety constraints. Following the identification of risks associated to CTSC projects progress, eighteen risks related to the phases prior to engineering were extracted. The aim was to put emphasis on the risks involved in the first phases of project development.

Risks with different natures were selected and modeled by the proposed methodology. Stakeholders of CTSC projects are considered as the controllers. Required control actions for each controller (and for each particular risk) were discussed. Subsequently, inadequate control actions that could lead to a hazardous state were reviewed. System dynamics models were presented to understand the feedback networks affecting the amplification of each risk.

Résumé (French Summary of Chapter 3)

Ce chapitre présente la méthodologie systémique proposée pour la gestion des risques des projets de CTSC. Il aborde les grandes lignes de la méthodologie qui est fondée sur les concepts de l’approche STAMP et de la dynamique des systèmes. L'objectif est de modéliser et d'analyser la structure de contrôle de sécurité impliquée dans un projet de CTSC. La structure de contrôle de sécurité est la structure organisationnelle des parties prenantes qui doivent maintenir les contraintes de sécurité. L'objectif de la structure de contrôle de sécurité dans cette thèse est d’éviter le retard de mis en œuvre ou l'échec des projets de CTSC. Cet objectif a été reformulé comme étant la définition et le management des risques majeurs qui pourraient affecter le maintien des contraintes de sécurité. Suite à l'identification des risques des projets de CTSC, dix-huit risques liés aux phases préalables de l'ingénierie ont été extraits. Le but était de mettre l'accent sur les risques associés aux premières phases de développement du projet.

Des risques de natures différentes ont été sélectionnés et modélisés en utilisant la méthodologie proposée. Les parties prenantes des projets de CTSC sont considérées comme des contrôleurs. Les actions de contrôle de chaque contrôleur (pour chaque risque) ont été examinées. Ensuite, les actions de contrôle inadéquates qui pourraient mener à un état potentiellement dangereux ont été évaluées. Les modèles de la dynamique des systèmes ont été présentés pour comprendre les réseaux de rétroactions affectant la transmission et l'amplification de chaque risque.

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Chapter 4: Application of the Methodology for Case Studies & Proposed Generic Safety Control Model

In this chapter, application of the methodology for three case studies is explained and discussed. The case studies are selected based on the level of project success.

The first example is Barendrecht, in the Netherlands, which was cancelled due to public opposition and lack of local support.

The second example is Lacq, as the first CTSC pilot plant in France, in which CO_2 injection is going on in spite of some technical challenges.

The third example is Weyburn, as a successful industrial scale EOR project in the North America, which has to deal with some questions.

As noted in chapter 3, going through details of case studies is impossible because of lack of information.

The chapter contains four sections. In the first section, the context of each case study is introduced. Major risks and challenges related to each project are also reviewed. The safety control structure of each project is presented subsequently. The aim is to study how (potential) losses could be avoided by assuring that safety constraints are maintained. The second section is devoted to the projects comparison in terms of context. The risks associated to the case studies are reviewed and compared in the third section. Discussions are provided in the last part in order to propose a generic safety control structure for CTSC projects. SWOT (Strengths, Weaknesses, Opportunities & Threats) analysis is selected to present an overview of positive and negative aspects of each project.

4.1 Application of the methodology for case studies

The aim of this section is to analyze the context and safety control structure of different projects to find the rules and elements leading to the progress of CTSC projects to commercial scales.

4.1.1 First example: Barendrecht

Barendrecht was a CTSC integrated project, planned to inject 400,000 tonnes CO_2 per year. CO_2 was produced in a hydrogen production plant and planned to be injected in two depleted gas fields. The capture plant is located about 20 km from Barendrecht, a town located in the west of the Netherlands (Figure 4.1). Barendrecht is situated at around 14 km of Rotterdam, the second largest city in the Netherlands. The population of the city is about 44,000 people.

Figure 4.1: Location of Barendrecht in the Netherlands [Zoekplaats, 2010]

A pipeline of 16.5 km was designed to transport the captured CO_2 to the storage location. The first gas field (Barendrecht) could store about 0.8 million tonnes of CO_2 at a depth of 1700 m. The second gas field (Barendrecht-Ziedewij) could store about 9.5 million tonnes of CO_2 at a depth of 2700 m.

Shell was the owner of the project, and a financial support of 30 million euros was invested by the government for this project. Shell would also have the benefit of emission saving under ETS (Emissions Trading System) program.

The tender was announced by the Dutch government in 2007. In early 2008, Shell was selected as the winner of the tender. Debates have begun from then on, when the project was presented to local community. The first phase of injection was planned to start in 2011 for a duration of three years. Injection in the second gas field was planned to begin in 2015 for 25 years. [Feenstra *et al.*, 2010]

In November 4th, 2010, Dutch Minister of Economic Affairs, Agriculture and Innovation announced that the project is cancelled. *The delay of the CO_2 storage project for more than 3 years and the complete lack of local support are the main reasons to* *stop*. However, the minister believes that Barendrecht experiences are valuable for further development of CO_2 storage in the Netherlands. So, *Barendrecht cancellation does not mean the end of CO_2 storage in the Netherlands*. [CCJ, 2010; Netherlands Government, 2010]

In this section, we will discuss the application of the methodology for Barendrecht project. The purpose is to understand the weaknesses of the project safety structure, and the points that could be improved to avoid the delay and stop.

The first two steps of the approach presented in Figure 3.2 are the same as the ones discussed earlier in section 3.1.2. Therefore, the central point of discussion in this part is the actors who play a role in the progress of the project.

In the following paragraphs, the main stakeholders and their responsibilities are summarized [Feenstra *et al.*, 2010]:

- National government: was engaged via two ministers: Ministry of Economic Affairs (EZ) and Ministry of Housing, Spatial Planning and Environment (VROM).
  EZ established a group (Task force CCS), with representatives of industry, NGOs and local governments, to support CTSC development in the Netherlands.
- Local governments: were involved at two levels: provincial and municipal.
  The executive board of the provincial government was responsible for environmental permitting procedures. An environmental protection agency (DCMR) was appointed by the provincial deputy to execute the leadership of a consultation group (BCO_2). BCO_2 was the administrative consultation group of Barandrecht project.
  At the municipal level, governments of Barendrecht and Albrandswaard were involved. Albrandswaard population did not raise many concerns about the project, probably because a few numbers of their houses were located directly above the gas fields. Barendrecht government was more actively involved.
- Project developers: Three companies were engaged. Shell was the initiator and responsible for storage and monitoring. Two other companies were collaborating with Shell for capture and transport. NAM (Netherlandse Aardolie Maatschappij BV), the Netherlands biggest oil and natural gas producer, was *responsible for existing natural gas production from the gas fields in Barendrecht*. OCAP (Organic CO_2 for Assimilation of Plants) was responsible for CO_2 transport.

- External experts, consultants and research organizations: Several external experts were involved, mainly by project developers, for environmental studies of CO_2 storage and to answer the questions from municipality in the public meetings.
- NGOs: Several NGOs were also active for or against the project. Greenpeace is opposed to CTSC, at national and international scales. Uncertainties about subsurface capacity to store CO_2, energy waste, risk of CO_2 leakage and expensiveness are the principal concerns of Greenpeace regarding CTSC technology [Rochon *et al.*, 2008]. SNM, the Netherlands Society for Nature and Environment, believes that CTSC is essential as an intermediate step towards clean energy.
- Local population: The people who live in the neighborhood of CO_2 storage location are significant stakeholders of CTSC projects. In Barendrecht case, they were represented by the municipal government.
- Media: Local and national newspapers, as well as televisions, websites and magazines were another actors who were involved in distributing information on the project.

The organizational structure of Barendrecht project is illustrated in Figure 4.2.

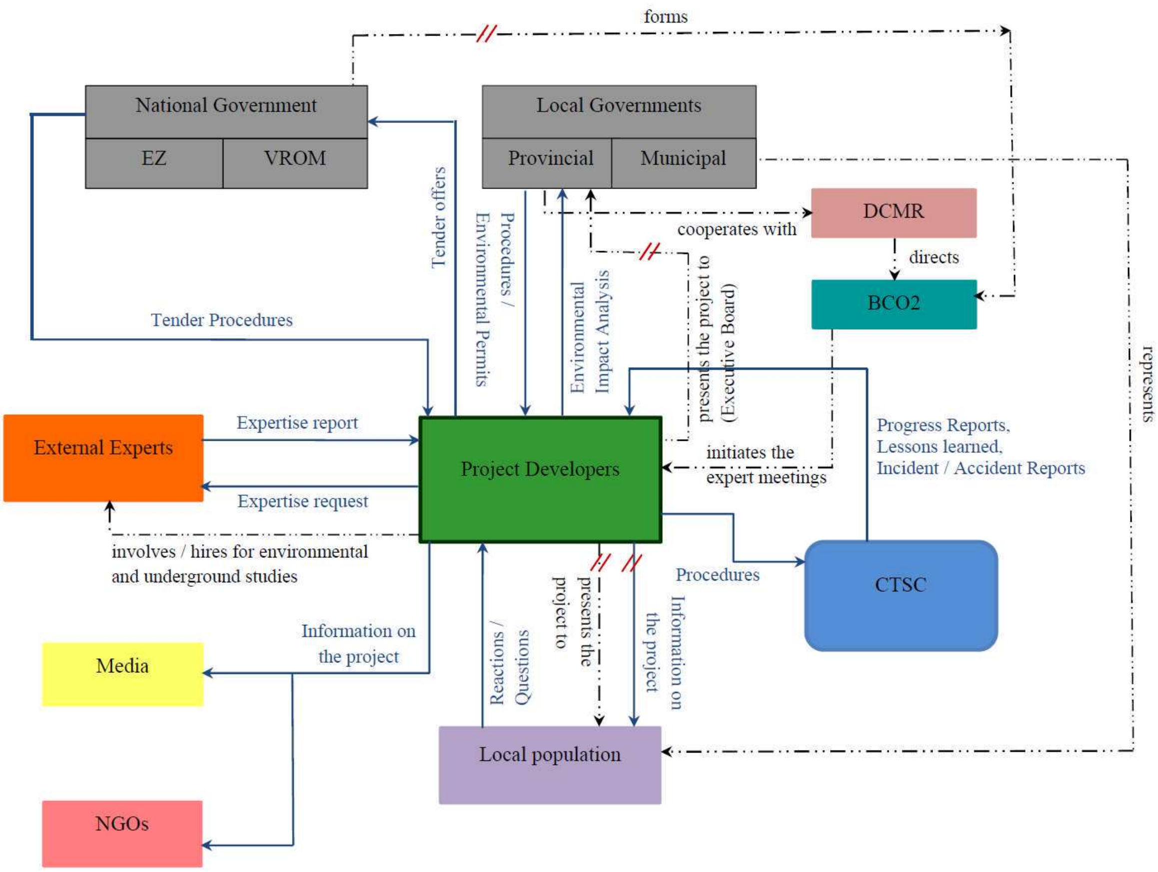


Figure 4.2: Barendrecht safety control structure, initial model

LEGEND

Stakeholders (Controllers) — Documents, deliverables and instructions

Physical Plant — Stakeholder connectors

// Delay

Rectangles with sharp corners symbolize the stakeholders (controllers), while the round-corner rectangle (CTSC) stands for the physical plant. (same legend as introduced in [Leveson, 2004b])

Dash lines are the stakeholders connectors, which show the relations of actors. A number of generic connector types have been proposed by [Dulac, 2007] and [Stringfellow, 2010]. Documents, deliverables and instructions exchanged between the actors are represented by solid lines.

// on the arrows represents delay, which is also a system dynamics concept (refer to section 2.1.2).

When delay symbol (//) is put on a connection, it means that the action is carried out with delay.

Lessons learned from the project confirm that communication problems are the main issues resulted in the opposition to the project. The most significant subjects affecting the effectiveness of the safety control structure are as following:

1. As showed in Figure 4.2, there is no connection between the national and local governments. The lack of such connection reinforced the public opposition.
2. Delays in some required actions made the community resist to the project. Some examples are presented in Figure 4.2. Establishment of the administrative consultation group (BCO_2) by the national government occurred rather belatedly, after the start of local opposition. Delay symbol on the connection between National Government and BCO_2 illustrates such late reaction. In addition, presentation of the project to the community (Local Governments and population) happened with delay. Some information on the project was not communicated upon request, especially due to confidentiality issues.
3. Regulatory responsibilities were not so clear in the project context. Changing the project regulatory framework was another reason for which the opposition occurred. In the new framework, the project would be considered as a one having national impacts. Therefore, National Government was authorized for all needed permissions, even those normally awarded by local governments.
4. Another issue is the lack of mutual connection between the stakeholders in some cases. For example feedbacks of local governments were not taken into consideration by the project developers, although the project had been presented to the local community.

   In some cases, mutual connections are not available for a particular reason. For instance, NGOs preferred to announce their opinion in the national level, instead of on this specific project. Therefore, no feedback is considered from NGOs to the project developers. The media also tried not to influence opinions. Thus, no direct connection is available from the media to the project developers.

An improved version of the project safety control structure (based on the 1st, 2nd and 4th abovementioned issues) is presented in Figure 4.3. The added elements are presented in orange. Delays existed in Figure 4.2 are removed in the proposed improved model (Figure 4.3).

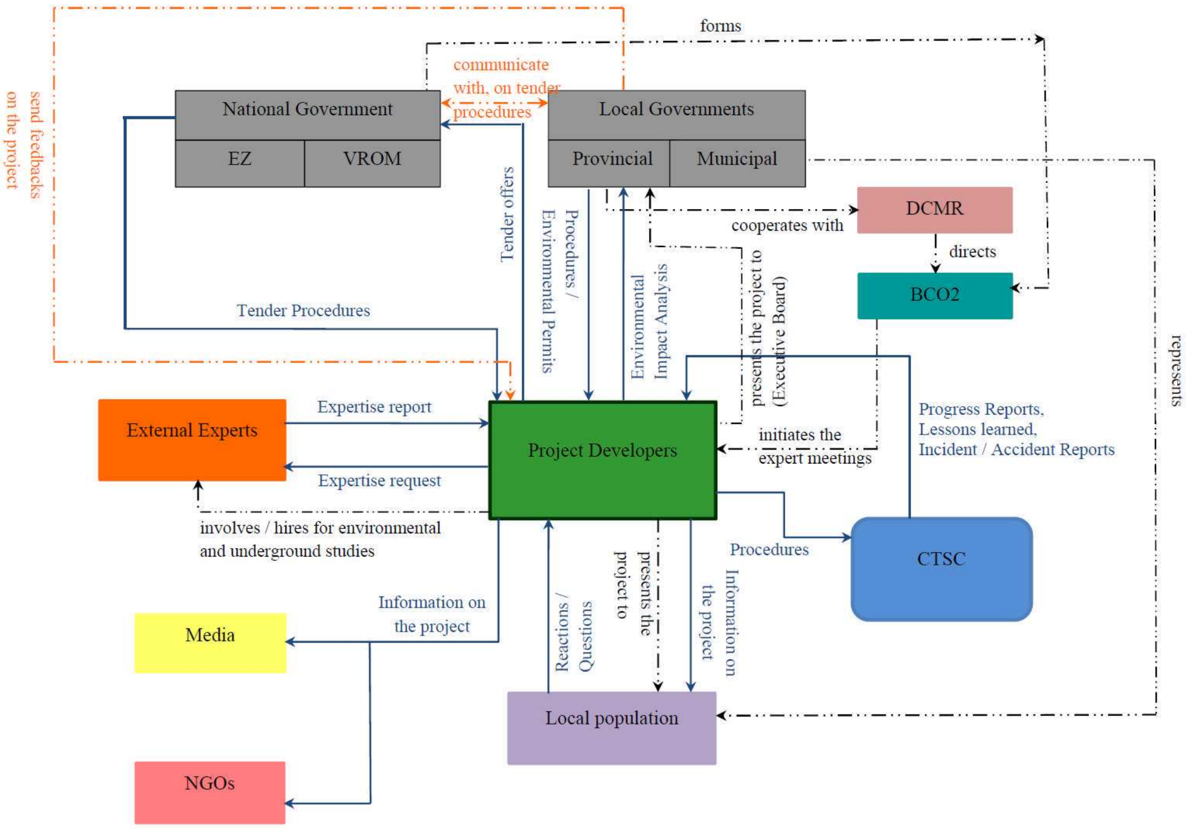


Figure 4.3: Barendrecht safety control structure, improved model

LEGEND

Stakeholders (Controllers) — Documents, deliverables and instructions

Physical Plant — Stakeholder connectors

Delay

4.1.2 Second example: Lacq

Lacq is a CTSC integrated pilot project in France to inject 120,000 tonnes CO_2 in a depleted gas reservoir (at a depth of 4500 m) during two years. The storage site is planned to be monitored during three years after the end of injection. Following the monitoring phase, the responsibility will be transferred to the government. It means that the project owner will not be responsible after these five years.

CO_2 is produced in a natural gas production unit which is situated in Lacq, a city in the South west of France in Pyrénées-Atlantiques region. An existing pipeline of 29 km transports CO_2 to the injection location, which is located in 3 km of Jurançon city. Around 7,000 people live in Jurançon (7087 in 2004 [Mairie Jurançon, 2012]). The Capture plant comes within ICPE regulation. The pipeline and the injection site come under the mining code.

In February 8, 2007, Total (the project owner) announced the decision of performing Lacq CTSC pilot plant in a news conference. From 6^{th} to 30^{th} of November 2007 a public dialogue was taken place to inform the local stakeholders on the project and understand their points of view and concerns. [C&S Conseils, 2008]

The regional government asked the project owner to conduct a public survey before giving the permits for the project start-up. A public survey was conducted for 64 days, from July 21, 2008 to September 22, 2008. A positive opinion on the project was given by the survey committee (at the end of October 2008) following the results of the survey.

On May 13, 2009, a decree was published by the regional prefecture to authorize the start of the project.

The injection was started in January 8, 2010 and planned to be terminated on April 2012. On September 12, 2011, Total requested an extension of 18 months for the injection, due to the technical problems of some equipment. In April 2011, 23,000 tonnes CO_2 was injected into the reservoir, while the objective was to inject 75,000 tonnes CO_2. [CLIS, 2011]

The major stakeholders of the project are as follows:

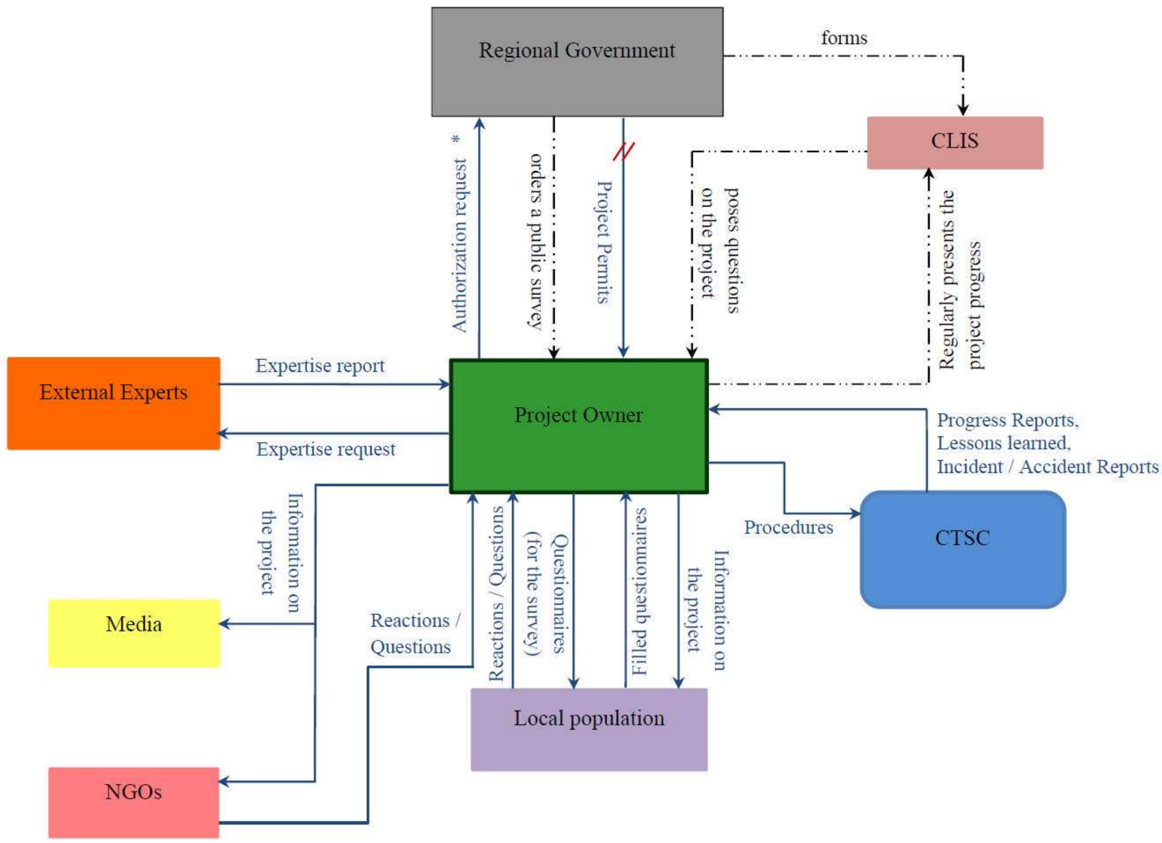
- Regional (Local) Government: Several representatives of the regional government are involved, including the prefects and DRIRE (Direction Régionale de l'Industrie, de la Recherche et de l'Environnement). Mayors and deputy mayors of different communities are also engaged.

DRIRE is a French governmental structure which is responsible for controlling the regulative compliance of the installation in ICPE framework (for ICPE definition, refer to section 1.6.1.1) [ICPE website 2]. Since January 2010, DRIRE has been merged with two other structures, DIREN (Direction Régionale de l'Environnement) and DRE (Direction Régionale de l'Equipement). These three merged structures form DREAL (Direction Régionale de l'Environnement, de l'Aménagement et du Logement). DREAL is conducted by the Ministry of Ecology, Energy and Sustainable Development (MEEDDM: Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la Mer).

A local committee (CLIS: Commission Locale d'Information et de Suivi) has been created by the regional prefecture to follow up the project progress. Regular meetings have been held since June 2008, when CLIS was established.

- Project Owner: Total is the owner of the project. Some other companies cooperate with Total, such as Air Liquide for the oxycombustion unit.
- External experts: from universities and research organizations have been requested to verify whether there are significant environmental and health risks concerning the project. If so, preventive and protective barriers for the potential risks were asked to be identified. The experts also seek to improve their knowledge on the possibility of commercial scale CTSC projects in France.
- NGOs: Several environmental NGOs have participated in the debates since the first public presentation of the project. An external specialist was asked by one of the NGOs to evaluate the project. Having one single private firm (Total) as the owner of the project is a main issue raised by the expert. He believes that for such a project, which has a life cycle much more than the company's life cycle, organizations working on long term monitoring and risk management have to contribute. [CLIS, 2008]
- Local population: is again a main stakeholder of the project.
- Media: Local and national newspapers and websites spread the information concerning the project.

The organizational structure of Lacq project is illustrated in Figure 4.4.



* Includes Environmental Impact Assessment, Hazard Analysis and HSE issues

Figure 4.4: Lacq safety control structure, initial model

LEGEND

	Stakeholders (Controllers)		Documents, deliverables and instructions
	Physical Plant		Stakeholder connectors
		//	Delay

Delay of the regional government to give the permits is due to the required time for consulting different organizations and obtaining their opinion on the project. It could last between 10 and 12 months [ICPE website 3]. Principal questions of CLIS from the project owner contain:

- The monitoring system of the project
- If the available protection barriers are sufficient to protect the local population

- The role of scientific committee (external experts) regarding the project

Contrary to the Barendrecht case, there is a lack of published information on Lacq organizational structure. Therefore, an improved safety control structure cannot be proposed for this particular case study.

A general improved structure will be suggested at the end of the chapter, when the case studies are discussed.

4.1.3 Third example: Weyburn

Weyburn is an oil field located in both Canada and the United States (Figure 4.5). The aim is to verify the feasibility of CO_2 geological storage under an Enhanced Oil Recovery (EOR) research project. The CO_2 is a byproduct of Dakota Gasification Company's synthetic fuel plant in North Dakota. The CO_2 is purchased from the fuel plant and is transported to Williston basin (Weyburn is a part of this basin) through a pipeline of 320 km. The first phase of injection was started on September 15, 2000. The initial injection rate was 5000 tonnes/day, and about 20 million tonnes of CO_2 is expected to be injected into the reservoir. Weyburn is a 180 km^2 oil field discovered in 1954. It is estimated that the oil production will increase by 130 million barrels (10% of the original oil in place) through the EOR operations. The oil field life is estimated to be increased by 25 years. [PTRC, 2004; Verdon, 2012]

Figure 4.5: Location of Weyburn CO_2 storage field [Verdon, 2012]

The project was launched by PTRC (Petroleum Technology Research Center), in Regina, Saskatchewan, in collaboration with Encana (now Cenovus) in Calgary, Alberta. The fund is provided by several governments and industries of Canada, the United States, Europe and Japan. [PTRC, 2004]

In January 2011, a farmer couple, having their land over the Weyburn CO_2 storage site, claimed that the injected CO_2 has been leaked, killed animals and *sent groundwater foaming to the surface like shaken-up soda-pop*. They asked a consultant (Petro-Find) for a soil gas study. The results showed that the source of CO_2 high concentrations in the soil is the injected CO_2 into the Weyburn reservoir. [CBC news, 2011]

PTRC and Cenovus, the project owners, called for an independent expertise. They announced that no leakage has been identified in the Weyburn field, and the source of CO_2 claimed by the farmers is not the Weyburn reservoir [Whittaker, 2011]. However, Ecojustice (a Canadian Environmental NGO) claims that there are important unanswered questions in PTRC response to the soil gas studies [Ecojustice, 2011]. In March 2011, Petro-Find performed another soil gas survey, and confirmed that the source of CO_2 found in the soil gas is the *anthropogenic CO_2 injected into the Weyburn reservoir* [Lafleur, 2011].

In spite of debates on the leakage, the project is still in operation [GCCSI website, 2012].

Details on Weyburn project stakeholders are not available. The following structure (Figure 4.6) is prepared based on [CCP, 2012], which is an industry point of view of stakeholders.

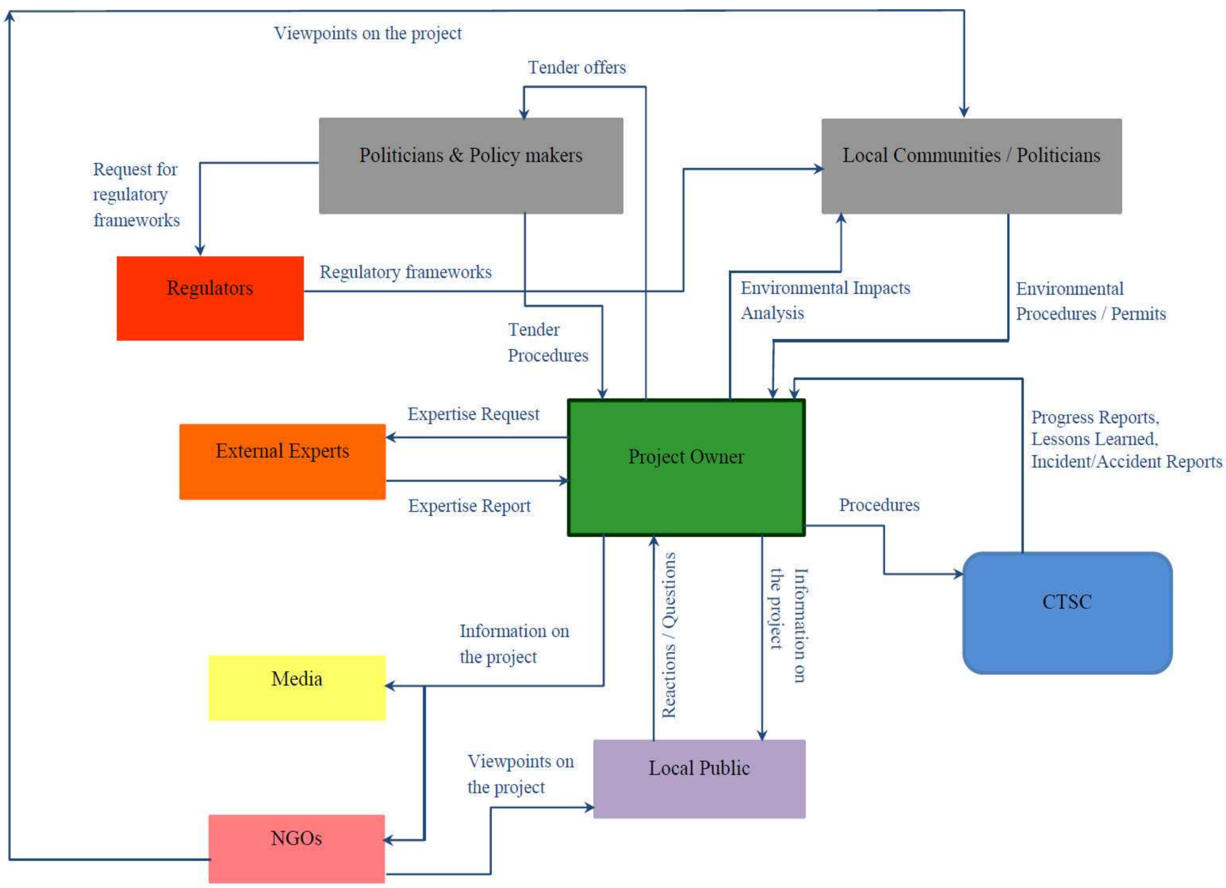


Figure 4.6: Weyburn safety control structure, rough model based on [CCP, 2012]

LEGEND

Stakeholders (Controllers) — Documents, deliverables and instructions

Physical Plant — Stakeholder connectors

// Delay

Similar to the case of Lacq, a great amount of information, especially on the organizational issues, are confidential, and consequently unavailable on Weyburn project.

Discussions of subsequent sections allow analyzing the positive and negative points of the case studies and proposing an optimized safety control structure for CTSC projects.

4.2 Comparison of case studies, from context point of view

As discussed earlier in previous chapters, risks are emergent properties of systems and therefore, have to be analyzed by taking into account the context in which they are generated. In addition, CTSC projects safety control structure is context specific and depends on several factors. For these reasons, it is essential to compare the case studies in terms of context.

Ashworth *et al.* assert that *it is challenging to compare case studies that have widely different technical, organizational and social characteristics* [Ashworth *et al.*, 2010]. Nevertheless, comparison of the three case studies (introduced in section 4.1) is provided in this part of the current report. The purpose is to propose an improved control structure for CTSC projects according to current available data. Lessons learned from further development of projects will provide useful information to improve and complete this analysis.

The three case studies do have several dissimilarities in terms of project phase, scale and the context in which they are/were working. The contexts of Barendrecht, Lacq and Weyburn projects are presented in Table 4.1.

Table 4.1: Comparison of case studies context

	Barendrecht	**Lacq**	**Weyburn**
Current Status	Cancelled (in detailed organization phase)	In operation	In operation
Scale	Demonstration	Pilot	LSIP
CO_2 storage rate	400,000 tonnes/year	60,000 tonnes/year	3 Mtpa
Storage type	Depleted gas field	Depleted gas field	EOR
Country	The Netherlands	France	The United States
Major issues	Public opposition	Technical challenges	- Public acceptance challenges - EOR as a long term storage option!
Main objective	Set down a foundation for CTSC LSIP in the Netherlands	Verify the feasibility of a CO_2 storage plant in France	Oil production increase
Concerning Industry	Oil & Gas	Oil & Gas	Oil & Gas

The following parameters (similarities or differences) are critical for the case studies:

1. **Scale:** The projects do not have the same scale in terms of CO_2 storage rate. Lacq is a pilot project, with the storage rate of 60,000 tonnes/year, while Weyburn is a Large Scale Integrated Project (LSIP with GCCSI definition, refer to section 1.2), which stores 3 million tonnes CO_2 per year. CO_2 storage rate in Barendrecht was 400,000 tonnes/year.
2. **Project main objective:** Being in different deployment scale, the projects deal with varied targets. The purpose of Lacq is to verify the feasibility of CO_2 storage in France, as well as testing the new oxy-combustion boiler. The aim of Barendrecht was to set down a foundation for large scale CTSC development in the Netherlands. In Weyburn, the objective is to increase the oil recovery.
3. **Concerning industry:** In all the three cases, Oil and Gas industry is involved. According to available statistics, power generation facilities are the most CO_2 emissive industries (refer to Appendix 3). However, only two of the fourteen operational large scale CTSC projects concern power generation industry [GCCSI, 2011a]. Oil and gas companies are currently more active in the domain. The question is why oil and gas industries are more interested in the investment on CTSC? The answer might be made from benefits point of view, which will be discussed later on in this chapter.

4.3 Comparison of case studies, from risk point of view

In chapter 3, a list of major CTSC project risks has been presented. If we compare the case studies in terms of associated risks, once again there are some sameness and several differences between Barendrecht, Lacq and Weyburn projects. The comparison is summarized in Table 4.2.

The first part of the table (risks 1-18) contains the risks concerning the phases prior to engineering. The second part (risks 19-39) includes the remainder.

Barendrecht was cancelled in the first phases of its progress. Consequently, the second group of risks is irrelevant to Barendrecht. The (potential) risks involved in the context of Lacq and Weyburn are much more numerous since these projects are in operation.

Table 4.2: Comparison of risks associated to case studies

Barendrecht	**Lacq**	**Weyburn**
☒ 1. Project permits not obtained ☒ 2. Technology scale-up ☒ 3. Public Opposition ☐ 4. Lack of knowledge/qualified resources for operating the unit ☒ 5. Legal uncertainties ☒ 6. Uncertainties in stakeholders requirements/perceptions - communication problems ☒ 7. Public availability of sensitive information ☒ 8. Change in policies/priorities ☐ 9. Financial crisis impact on financial support of CCS projects ☐ 10. Unavailability of a monetary mechanism for CO_2 ☐ 11. Geographical infrastructure ☐ 12. Lack of financial resources ☒ 13. Lack of political support ☐ 14. High cost of project ☐ 15. Unavailability of regulations regarding different types of storage (offshore/onshore) ☐ 16. Uncertainties regarding the storage performance (capacity/injectivity/containment) ☐ 17. Model and data issues ☐ 18. Uncertainties related to storage monitoring	☐ 1. Project permits not obtained ☒ 2. Technology scale-up ☒ 3. Public Opposition ☒ 4. Lack of knowledge/qualified resources for operating the unit ☒ 5. Legal uncertainties ☒ 6. Uncertainties in stakeholders requirements/perceptions - communication problems ☒ 7. Public availability of sensitive information ☒ 8. Change in policies/priorities ☐ 9. Financial crisis impact on financial support of CCS projects ☐ 10. Unavailability of a monetary mechanism for CO_2 ☐ 11. Geographical infrastructure ☐ 12. Lack of financial resources ☐ 13. Lack of political support ☐ 14. High cost of project ☐ 15. Unavailability of regulations regarding different types of storage (offshore/onshore) ☒ 16. Uncertainties regarding the storage performance (capacity/injectivity/containment) ☒ 17. Model and data issues ☒ 18. Uncertainties related to storage monitoring	☐ 1. Project permits not obtained ☐ 2. Technology scale-up ☒ 3. Public Opposition ☐ 4. Lack of knowledge/qualified resources for operating the unit ☒ 5. Legal uncertainties ☒ 6. Uncertainties in stakeholders requirements/perceptions - communication problems ☒ 7. Public availability of sensitive information ☐ 8. Change in policies/priorities ☐ 9. Financial crisis impact on financial support of CCS projects ☐ 10. Unavailability of a monetary mechanism for CO_2 ☐ 11. Geographical infrastructure ☐ 12. Lack of financial resources ☐ 13. Lack of political support ☐ 14. High cost of project ☐ 15. Unavailability of regulations regarding different types of storage (offshore/onshore) ☐ 16. Uncertainties regarding the storage performance (capacity/injectivity/containment) ☒ 17. Model and data issues ☒ 18. Uncertainties related to storage monitoring

Table 4.2: Comparison of risks associated to case studies, continued

Barendrecht	**Lacq**	**Weyburn**
☐ 19. Corrosion ☐ 20. Using the existing facilities (specially pipelines) ☐ 21. CO_2 out of specification ☐ 22. CO_2 plumes exceed the safe zone ☐ 23. Safety related accident ☐ 24. Construction field conditions ☐ 25. Proximity to other industrial plants ☐ 26. Energy consumption ☐ 27. Maintenance and control procedures (including ESD system) ☐ 28. BLEVE ☐ 29. Phase change & material problems ☐ 30. Lower Capture efficiency due to the upstream plant flexible operation ☐ 31. CO_2 leakage from compression unit ☐ 32. Pipeline construction ☐ 33. CO_2 leakage from pipeline ☐ 34. Leakage through manmade pathways such as abandoned wells ☐ 35. Well integrity ☐ 36. CO_2 migration ☐ 37. Injectivity reduction over time ☐ 38. CO_2 leakage from storage to the surface ☐ 39. Soil contamination	☒ 19. Corrosion ☒ 20. Using the existing facilities (specially pipelines) ☒ 21. CO_2 out of specification ☒ 22. CO_2 plumes exceed the safe zone ☒ 23. Safety related accident ☐ 24. Construction field conditions ☐ 25. Proximity to other industrial plants ☒ 26. Energy consumption ☒ 27. Maintenance and control procedures (including ESD system) ☐ 28. BLEVE ☒ 29. Phase change & material problems ☒ 30. Lower Capture efficiency due to the upstream plant flexible operation ☒ 31. CO_2 leakage from compression unit ☐ 32. Pipeline construction ☒ 33. CO_2 leakage from pipeline ☒ 34. Leakage through manmade pathways such as abandoned wells ☒ 35. Well integrity ☒ 36. CO_2 migration ☒ 37. Injectivity reduction over time ☒ 38. CO_2 leakage from storage to the surface ☒ 39. Soil contamination	☒ 19. Corrosion ☐ 20. Using the existing facilities (specially pipelines) ☒ 21. CO_2 out of specification ☒ 22. CO_2 plumes exceed the safe zone ☒ 23. Safety related accident ☐ 24. Construction field conditions ☐ 25. Proximity to other industrial plants ☒ 26. Energy consumption ☒ 27. Maintenance and control procedures (including ESD system) ☐ 28. BLEVE ☒ 29. Phase change & material problems ☒ 30. Lower Capture efficiency due to the upstream plant flexible operation ☒ 31. CO_2 leakage from compression unit ☐ 32. Pipeline construction ☒ 33. CO_2 leakage from pipeline ☒ 34. Leakage through manmade pathways such as abandoned wells ☒ 35. Well integrity ☒ 36. CO_2 migration ☒ 37. Injectivity reduction over time ☒ 38. CO_2 leakage from storage to the surface ☒ 39. Soil contamination

Causal graphs illustrating the interactions of risks (Table 4.2) are presented in Figures 4.7, 4.8, 4.9 and 4.10. The risks for which evidences/references are available are highlighted in green bold, while risks having the potential to affect the projects are represented in violet. To avoid models complexity, interactions of all thirty nine risks are not shown in the figures.

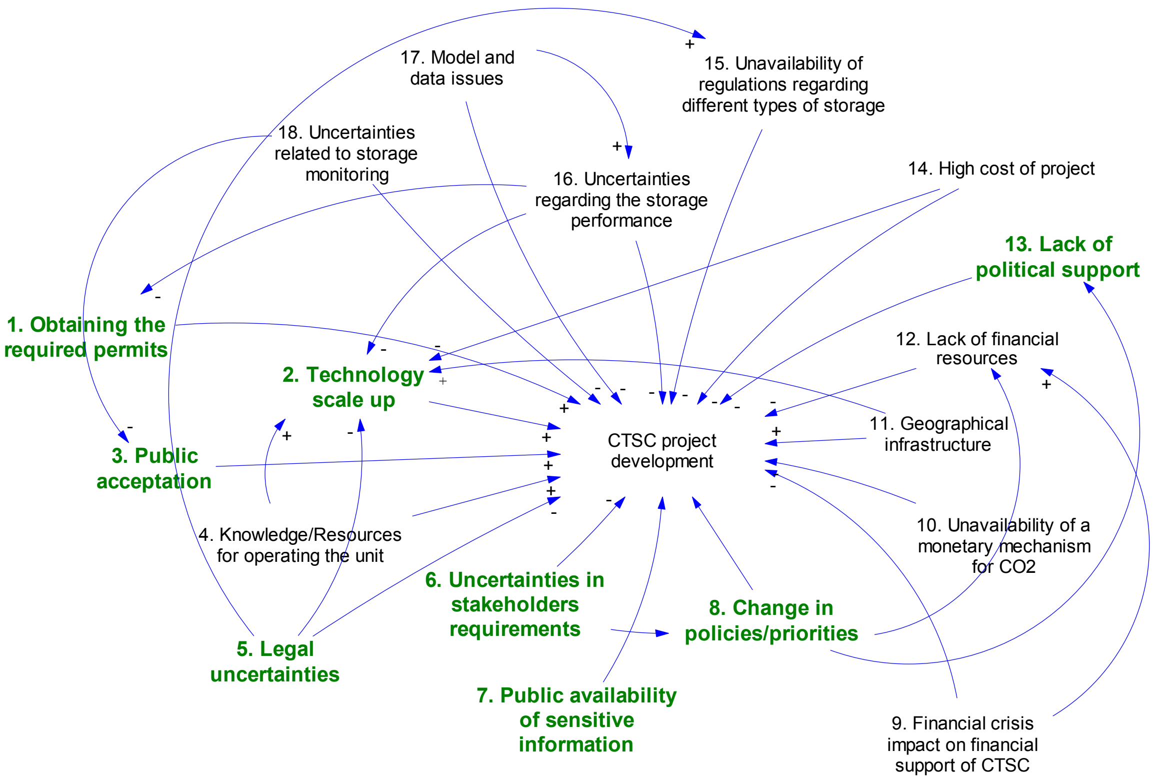


Figure 4.7: Interconnections of major risks affecting Barendrecht project progress

The areas of concern in Barendrecht safety control structure (responsible for maintaining the safety constraint i.e. providing required control measures to avoid project delay or stop) have been reviewed in section 4.1.1. These issues could be explained as inadequate control actions led to the project failure (hazardous state).

As presented in the control structures of section 4.1, project owner is at the heart of the structure in all the cases. Project owner is always an endogenous controller who is in interrelation with other controllers to assure the availability of required control measures.

Some general inadequate control actions have been already discussed in section 3.2. The ones related to Barendrecht project failure are summarized in Table 4.3.

Table 4.3: Principal Inadequate Control Actions leading to Barendrecht project failure

Principal Inadequate Control Actions leading to Barendrecht project failure:
- Delay in presenting the project to the community - Avoiding to share certain (confidential) information - Delay in providing feedback on stakeholders concerns or questions - Unavailability of communication between some stakeholders, such as national and local governments - Unavailability of a correctly specified regulatory framework

Barendrecht example confirms that all potential interconnections are not identified in the risk network (Figure 4.7). Lessons learned from the project assert that legal uncertainties/modifications, uncertainties in stakeholders requirements and lack of political support could lead to public opposition. Hence, Figure 4.7 should be modified as follows (Figure 4.8), by adding new feedbacks.

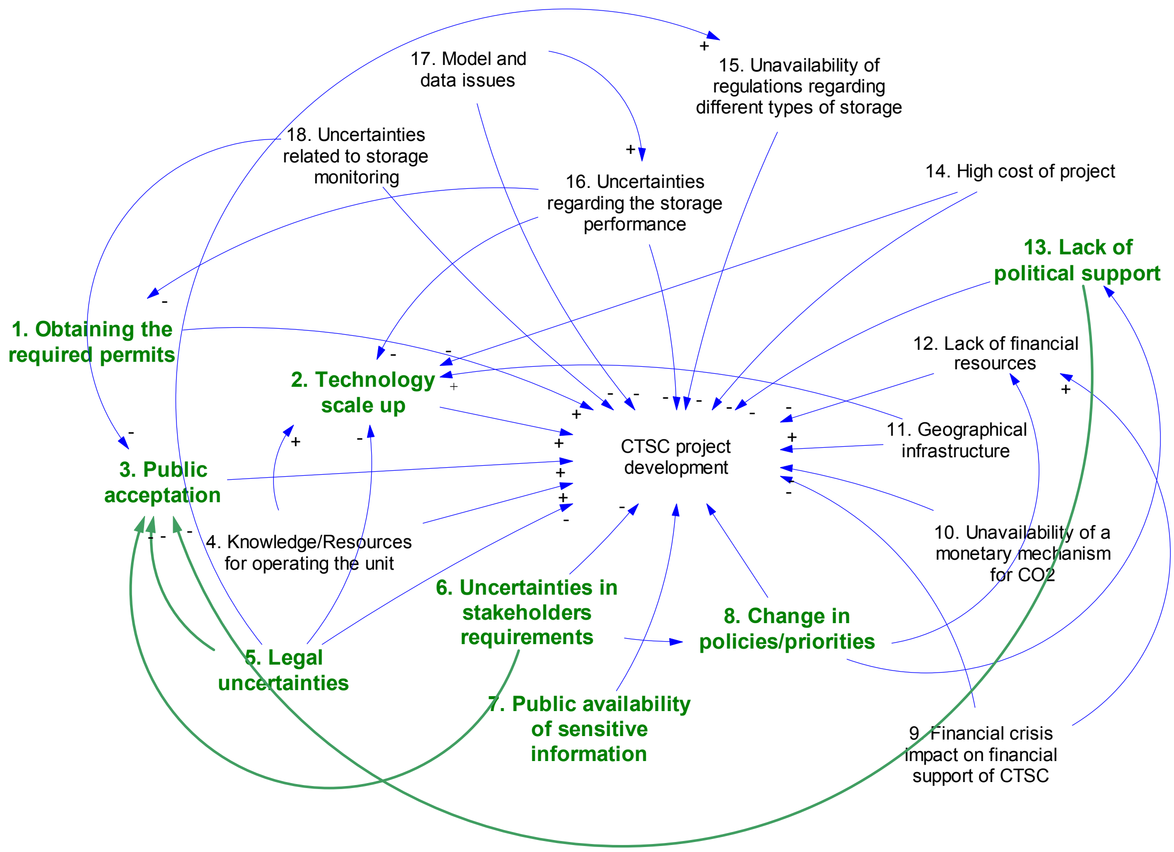


Figure 4.8: Interconnections of major risks affecting Barendrecht project progress, modified according to lessons learned

The importance of public perception is supported by [CCP, 2012] that notes: *if the general public is not supportive of, or is even actively opposed to, a new technology, it can become politically and/or socially unacceptable*. CCP report also underline the role of local communities and the fact that *local communities can also create significant delays to projects, not only by influencing permitting processes, but also by physically restricting activities with demonstrations or blockades if there are significant levels of concern about a project*.

The (potential) risks involved in Lacq project context are illustrated in Figure 4.9. The risks for which evidences/references are available are highlighted in green bold. Potential risks are represented in violet.

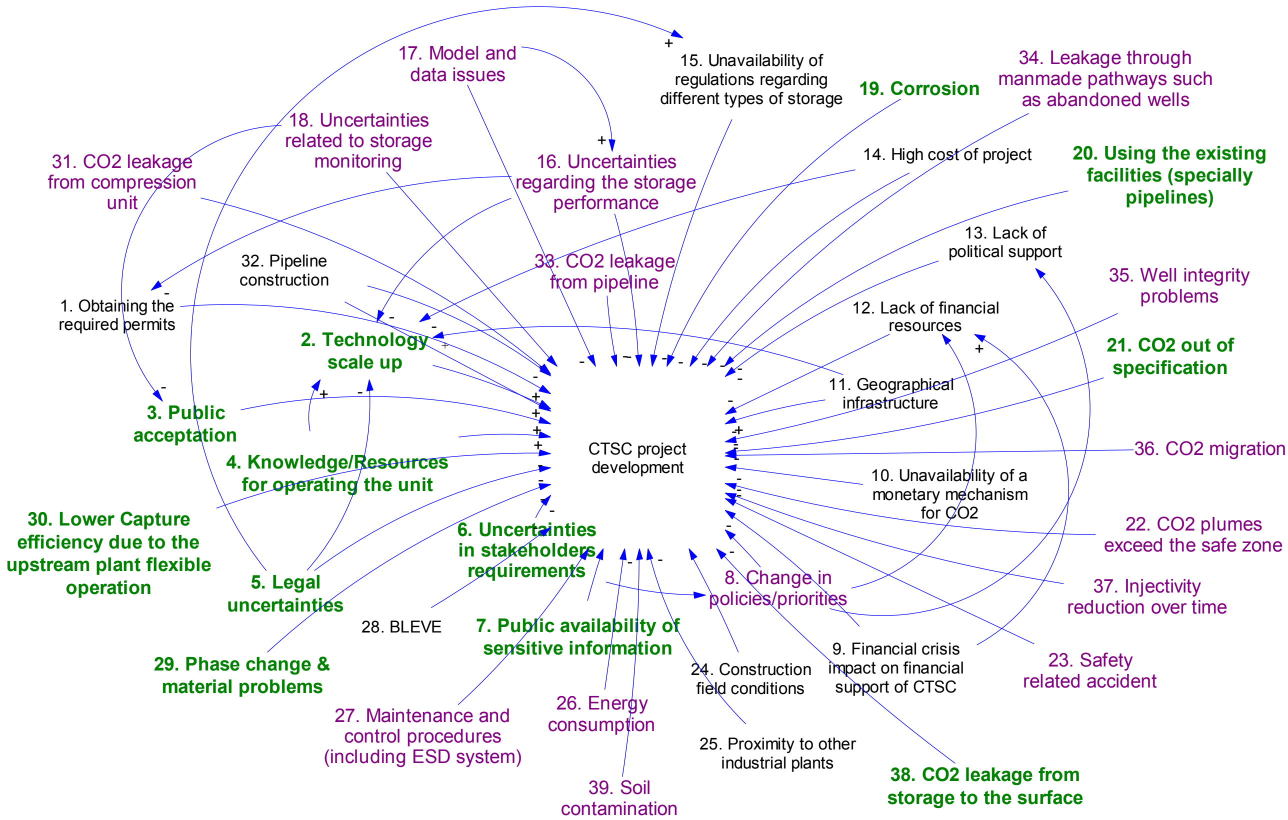


Figure 4.9: Interconnections of major risks affecting Lacq project progress

Lacq project have neither the same objectives nor the same scale as Barendrecht. Nevertheless, analysis of Lacq project context allows us to identify major (potential) inadequate control actions that could lead to delay or failure of the project. Available information and lessons learned from the project provide us with some inadequate control actions resulted in project delay. Some of the inadequate control actions might be justified by the fact that the project is in pilot scale, and technical challenges are indispensable for verifying CTSC feasibility in this scale. Since the project is not terminated, potential inadequate control actions could be also envisaged (Table 4.4).

Table 4.4: Principal (Potential) Inadequate Control Actions leading to Lacq project delay or failure

Principal Inadequate Control Actions leading to Lacq project delay:
- Underestimation of feed impurities that could result in corrosion - Using some existing facilities which are not appropriate for the current application - Having to send forth the CO_2 into the atmosphere as a result of technical problems
Principal Potential Inadequate Control Actions leading to Lacq project delay or failure:
- Avoiding to share certain (confidential) information - Avoiding to take the effects of using existing facilities into consideration

Figure 4.10 illustrates the (potential) risks associated to Weyburn project. Same as the previous cases, the risks for which evidences/references are available are highlighted in green bold. Potential risks are represented in violet.

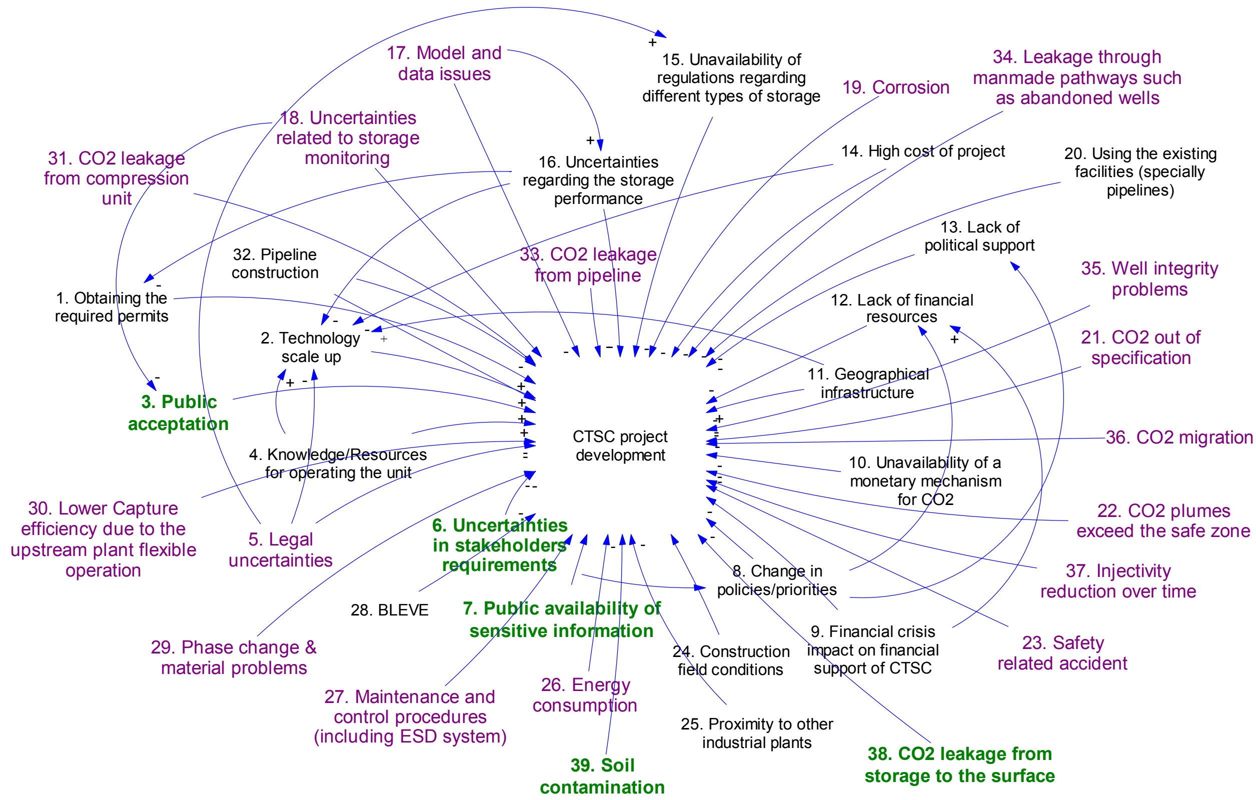


Figure 4.10: Interconnections of major risks affecting Weyburn project progress

Weyburn case is totally different from Barendrecht and Lacq, not only due to its geopolitical context but also because Weyburn is an EOR (Enhanced Oil Recovery) project. EOR is addressed as a CO_2 reuse option rather than a long term storage by some experts. The project is one of the Large Scale Integrated Projects which is currently in operation, even so a number of stakeholders have still some unanswered questions on the project.

Weyburn has recently experienced an opposition due to a leakage claim made by a farmer (refer to section 4.1.3). Attempts were made by the project owners and independent experts to study the sources of leakage. For the moment, there is not a mutual agreement on this subject. According to available documents, local community has different opinions on the project. The project is generally appreciated by the community. Nevertheless, there are some uncertainties supposed to be clarified by the project owners.

Mayor of Weyburn, who has a deep familial connection to the city, is a proponent of the project. She considers Weyburn CTSC project as an opportunity for the community. She defends her idea by highlighting employment opportunities and rise in real estate business costs as positive effects of the project. The mayor believes that no safety risk is probable in long term according to the researches. Natural resources (coal) and available knowledge (on oil and gas industry) are additional points that make Weyburn an appropriate location for CO_2 storage experience [CCS101, 2009a].

On the other hand, the reeve of Weyburn rural municipality is *cautiously optimistic* about the project. As well as the mayor, she has a farm family with an ancient familial background in Weyburn area. In spite of being *optimistic* about the project, she is *cautious* because she *doesn't feel that she knows a lot about the long term effects. There are still some unknown factors.* The reeve makes reference to a panel organized by PTRC. She affirms that they *maybe don't have the answers that people want for those questions on long term risks*. Therefore, it is not currently obvious whether the gains from the project are short term or long term. Even if some people will come to Weyburn for working in the industry, others may leave the region because of the CO_2 storage project. The positive points are the *economic drivers* and benefits such as recovering oil (which will lead to *expand high additional employees*), *media attention* and tourism increase. Nevertheless, she (as both a local administration officer and a farmer) has several personal concerns. She believes that *Weyburn does rely on oil*, although agriculture is another important industry in Weyburn. Her concerns include:

- Impact of the storage on land values
- Impact of the storage on water systems
- Impact of the storage on live stock
- Impact of the storage on land production performance

And she doubts whether Weyburn project is a long term storage facility since oil is recovered as a result. [CCS101, 2009b]

These expressions attest that each stakeholder is seeking for his own individual benefits in CTSC project development. Searching for benefits (especially short-term benefits) explain why oil and gas industry is currently investing more on CTSC technologies.

Being an EOR project is a critical factor of success for Weyburn. GCCSI confirms that EOR is a significant CO_2 reuse option which has a substantial contribution to CTSC projects development. Nine from fourteen CTSC projects currently in execution or operation phase are EOR ones [GCCSI, 2011a, b]. As noted in section 4.1.3, oil production of Weyburn will increase by 130 million barrels (10% of the original oil in place) as a result of EOR operations.

(Potential) inadequate control actions concerning Weyburn project are summarized in Table 4.5.

Table 4.5: Principal (Potential) Inadequate Control Actions leading to Weyburn project delay or failure

Principal Inadequate Control Actions involved in Weyburn project context:
- Incapability to answer the stakeholder questions - Underestimating local population concerns
Principal Potential Inadequate Control Actions leading to Weyburn project delay or failure:
- Avoiding to share certain (confidential) information - Avoiding to take local community concerns into account

Context and risks related to Barendrecht, Lacq and Weyburn projects were analyzed in sections 4.2 and 4.3. Main (potential) inadequate actions resulting in the project delay or failure were also introduced.

In the next section, we will discuss what can be learned from these examples, and a general improved safety control structure will be proposed for CTSC projects.

4.4 Discussions and proposed safety control structure for CTSC projects

Reviewing (potential) inadequate control actions of the projects, presented in Tables 4.3, 4.4 and 4.5, direct us to the conclusion that a systematic communication among stakeholders is essential from the very first phases of the project.

CO_2 capture project (CCP) has published a report on the issues and concerns of CTSC stakeholders [CCP, 2007]. Six major issues have been pointed out:

- Deployment cost
- Deployment scale
- Perceived risks
- Lack of accessible information

- Supporting policies
- Adequacy of regulatory frameworks

Perceptions of several stakeholders from different geographical zones (Australia and New Zealand, North America, Europe, Japan, China, India and South Africa) are presented in this report. The stakeholders include:

- Research and Development organizations
- Industry
- Government
- NGOs
- General public

The results confirm that most of the stakeholders are worried about cost of deployment, deployment scale, impact on drinking water, accessibility of information according to the stakeholders requirements and adequacy of regulatory frameworks in North America. However, concerns of stakeholders in Europe are much more less than the North American ones. Regulatory issues are at the top of European stakeholders considerations. Most of the concerns have been raised by NGOs, both in North America and Europe.

The most challenging points on which there are strong difference of opinions within stakeholder groups include:

- Stakeholder perceptions on CTSC as a bridging technology
- Impact of EOR on oil market extension
- Impact of CTSC on coal market extension
- Effect on investments on other energy sources such as renewables and nuclear
- Contribution of CTSC to CO_2 emissions reduction in short term
- Inadequacy of efforts for communication
- Cost of deployment

These points have been mostly raised in North America. [CCP, 2007]

A report has been recently published by CO_2 Capture Project (CCP). Different case studies and publications have been reviewed in order to identify the concerns of stakeholders. CCP mentions that most of CTSC case studies relate to oil and gas industry rather than power generation. Therefore findings are based on oil and gas sector stakeholder viewpoints. According to [CCP, 2012], policy makers, local community and regulators are the most significant stakeholders for project development. It should be noted that the report of CCP has been written from industry point of view. The priorities named by CCP include:

- HSE issues
- *Awareness and acceptance* of CTSC
- Technical concerns
- *Commercial and local development benefits*
- *Policy and legal issues*
- *Diversion of resources away from renewable energy*
- CTSC *positive and negative impacts on climate change*
- *Groups with variable positions* on CTSC and *issues of concern*

The recent priorities are more or less similar to the ones published by CCP in 2007. Areas of concern of different stakeholders are available in Appendix 5.

Another critical factor brought forward by CCP is CTSC investors different motivations. Governments, banks and industries are the main investors of the technology who are also seeking their own benefits.

In this connection, examples are available for the projects which have been failed due to financial restrictions or uncertainties. A recent one is Longannet project in the United Kingdom.

CTSC is one of the options included in the UK energy policy to reduce CO_2 emissions from the energy sector. Nuclear power generation plants, renewable sources and improving energy efficiency are the other choices of the UK energy policy.

The competition for the UK first CTSC demonstration project was launched in 2007. Contract award and project operation were scheduled for 2009 and 2014 respectively. Longannet was one of these projects. From the nine first bidders, four were selected. Three of them left the competition by October 2010. In October 2010, a capital budget of £1 billion was awarded to the Department of Energy and Climate Change (DECC), by the Treasury, to be invested on CTSC. However, the estimated capital cost of the project was £1.9 billion (by DECC, in July 2010). Since the project was not affordable with the agreed £1 billion, DECC terminated the negotiations with the only remained bidder (a consortium of Scottish Power, National Grid and Shell) in October 2011. £64 million was spent by DECC from November 2007 to October 2011, including £40 million for two bidders FEED contracts.

UK National Audit Office has recently published a report in which the grounds for Longannet project unsuccessfulness are analyzed [Thomas *et al.*, 2012]. Key findings of the report are as follows:

1. DECC underestimation of the cost of CTSC project
2. Economic, policy and regulatory uncertainties (Simultaneous development of the UK energy policy and CTSC competition)
3. Insufficient experience of the government to deal with projects in such scale
4. Not reviewing alternate options by the government, such as developing smaller scale projects to analyze different aspects of the technology. The question is *how a single demonstration project would contribute to policy objections?*
5. DECC underestimation of commercial risks of the project
6. Limited number of bidders as a result of limited requested specifications (post-combustion capture at a coal-fired power plant of 300 Megawatts)
7. DECC underestimation of significant issues pointed out in external reviews

Going back to our case studies, the analysis could be presented within the framework of a SWOT Matrix. SWOT is an acronym for Strengths, Weaknesses, Opportunities and Threats. *SWOT analysis is a strategic planning tool used to evaluate the strengths, weaknesses, opportunities, and threats involved in a project or in a business venture. It involves specifying the objective of the business venture or project and identifying the internal and external factors that are favorable and unfavorable to achieving that objective. The technique is credited to Albert Humphrey, who led a research project at Stanford University in the 1960s and 1970s using data from Fortune 500 companies. SWOT allows analysts to categorize factors into internal (strengths, weaknesses) or external (opportunities, threats). One of the main limitations of this approach, however, is that the importance of each factor in decision-making cannot be measured quantitatively, and it is difficult to assess which factor has the greatest influence on the strategic decision* [Arslan & Deha Er, 2008]. A comparison of SWOT analysis with different hazard analysis methods such as HAZOP (HAZard and OPerability), What/if

Analysis, FMEA (Failure Modes and Effects Analysis), FTA (Fault Tree Analysis) and ETA (Event Tree Analysis) is provided in [Arslan & Deha Er, 2008].

In the current work, SWOT matrices are another form of presenting inadequate control actions. The questions that have to be answered to define the strengths, weaknesses, opportunities and threats of each CTSC project are presented in Figure 4.11.

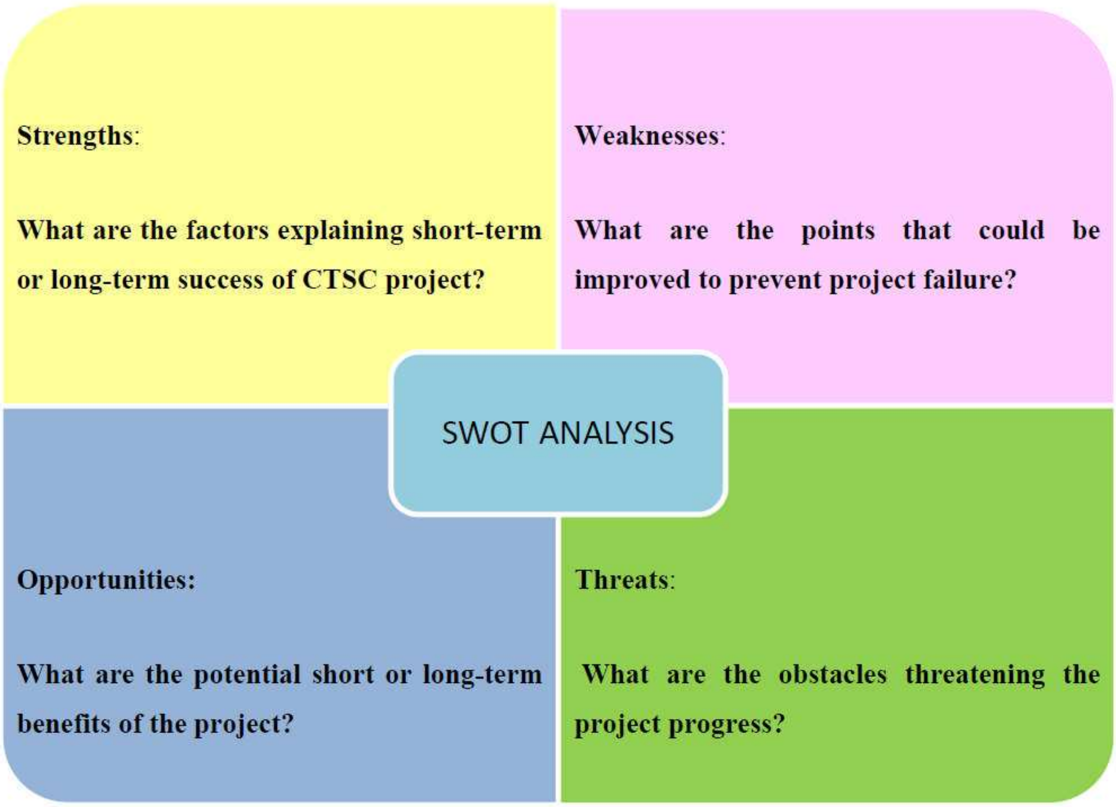
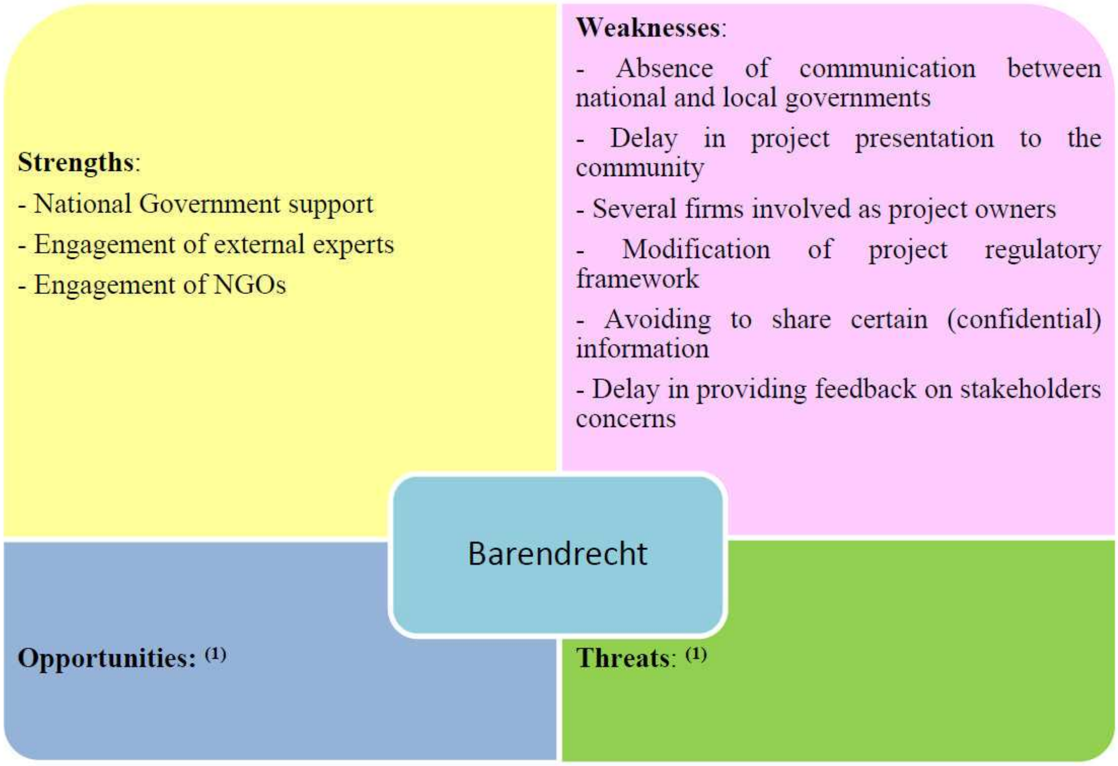


Figure 4.11: Model of a CTSC Project SWOT Analysis

SWOT matrices of the three case studies are illustrated in Figures 4.12, 4.13 and 4.14 in order to provide more comprehensible information for some audience of the current report. Opportunities and Threats are not mentioned for Barendrecht since the project has been cancelled.



(1) Opportunities and Threats are not mentioned for Barendrecht since the project has been cancelled.

Figure 4.12: SWOT Analysis, Barendrecht Project

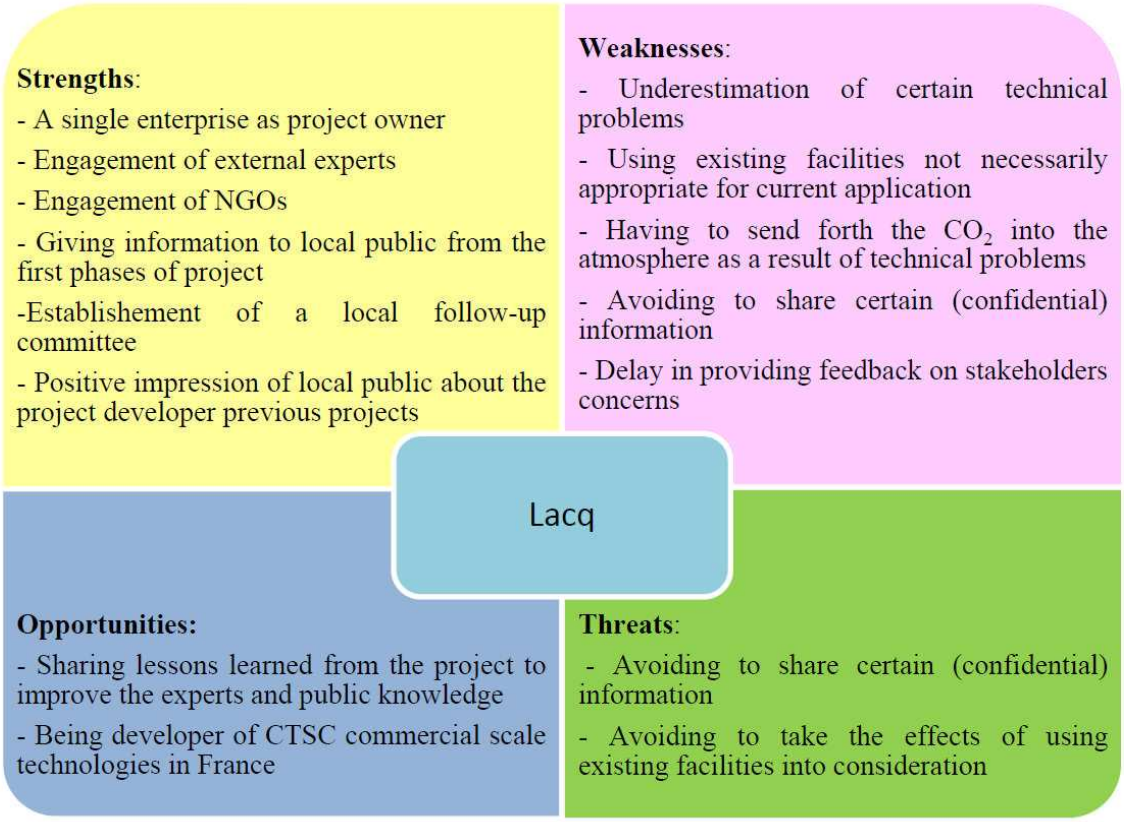


Figure 4.13: SWOT Analysis, Lacq Project

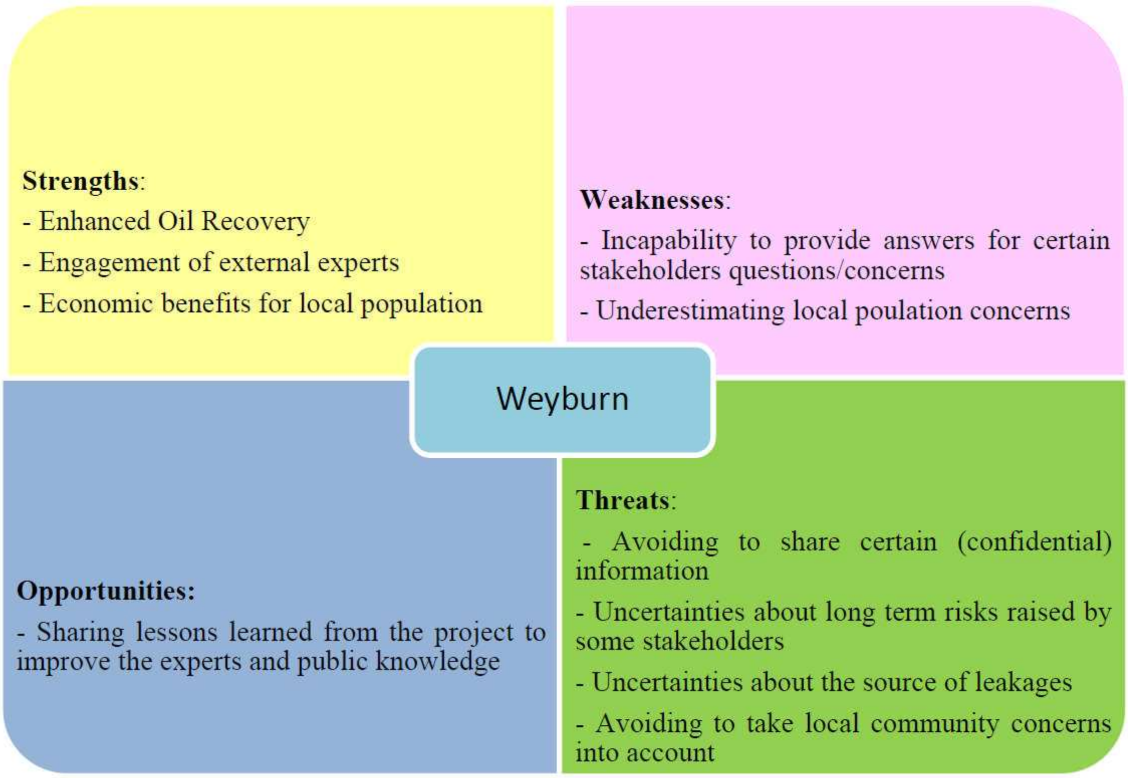


Figure 4.14: SWOT Analysis, Weyburn Project

Twelve factors have been recently proposed by IRGC, having the capacity to create an appropriate context for emerging risks (already introduced in section 2.3.4).

“*Conflicts about interests, values and science*” is one of these factors. Authors of IRGC report state that emerging risks may be intensified when opposition occurs *on the grounds of contested science or incompatible values*. They argue that people have subjective views about the science according to their own values. Hence, in case of conflicts, interests and values of involved stakeholders should be clarified. Examples are presented for both successful and failed attempts to *block a technology or industrial facility*. The positive one is the conflicts on potential risks of LNG terminals, which are managed successfully in the Netherlands *through creative use of public participation and local discussion*. In the contrary, the US nuclear waste management is termed as a *failed* example.

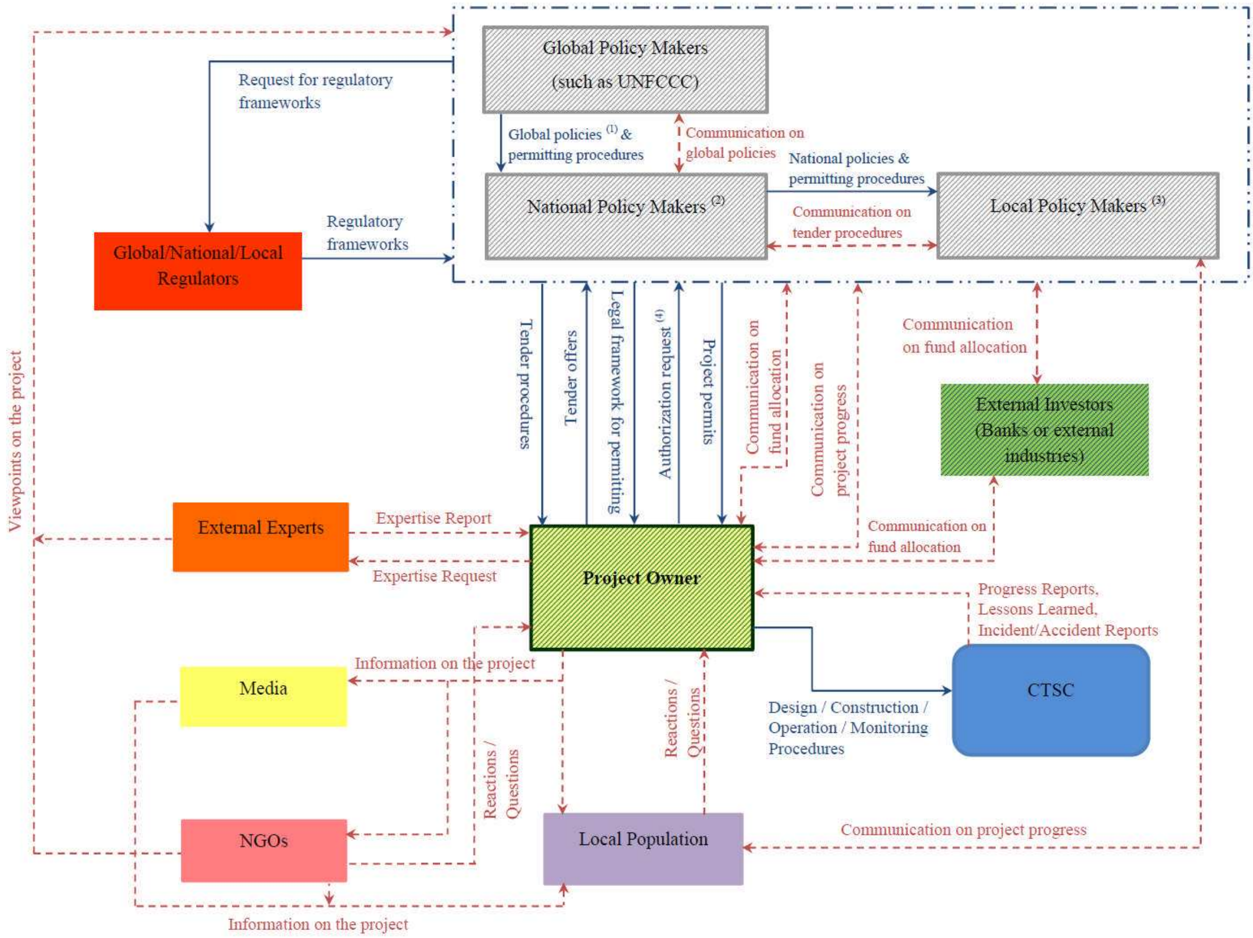
“*Social dynamics*” is another critical factor. *Societies are continually evolving. As complex systems, they may adapt to new or changing technologies … However, they sometimes fail to adapt*. It is reasoned that social dynamics are not *directly controllable* but may be *influenced* in order to mitigate emerging risks. [IRGC, 2010]

Internal and external communication can also affect emerging risks intensification; internal communication between the actors involved in risk management, and external communication of these actors with the public. IRGC report underlines varied concerns of people and scientists/regulators concerning CO_2 Capture and Storage. Some people are worried about safety risks and ground water contamination while others are more concerned about the cost, *the effect on their electric rates* and *property values* [IRGC, 2010]. Communication allows improving risk management process by integrating all stakeholder concerns.

When some stakeholders have got certain information about risks that is not available to others, “*information asymmetries*” occur. In some cases, such as the ones related to national security, information asymmetries are unavoidable. However, unavailability of information for risk managers could lead to the negligence of prevention or protection barriers in risk management process. Therefore, *the identification and evaluation of information asymmetries is important in the governance of emerging risks*.

Communication is known as a key factor that could affect all other factors. [IRGC, 2010]

A general safety control structure is proposed according to the analysis of the case studies (Figure 4.15). The Figure confirms the importance of communication among stakeholders. *An iterative and interactive dialogue between the key stakeholders is also recommended* by [Koornneef *et al.*, 2012] *to ensure that state of the art knowledge is included in the risk management of storage projects*.



(1) Global policies according to regulatory frameworks
(2) Including Policy Makers in the scale of zones (EU, US, etc.) and countries
(3) Including Policy Makers in the scale of regions and communities
(4) Including EIA, Hazard Analysis and HSE concerns

Figure 4.15: Proposed Safety Control Structure for CTSC projects

LEGEND

Stakeholders (Controllers) — Documents and information, not necessarily exchanged dynamically

Physical Plant — Dynamically interchanged documents / actions

Potential Investors

In Figure 4.15, solid lines represent documents and information exchanged between the stakeholders, not necessarily in a dynamic manner. Dash lines show the flow of dynamic interchange, i.e. what should be maintained throughout the project life.

Global, National and Local Governments are regrouped in a box, since the relationship of other stakeholders with the governments is varied in different regions.

Regulators are asked by Policy Makers for regulatory frameworks. Global policies and permitting procedures are defined (by Global Policy Makers) for CTSC according to regulatory frameworks and climate change policies. National policies and permitting procedures are transposed to national contexts by National Policy Makers, who shall be continuously in communication with Global and Local Policy Makers.

Tender procedures are sent to the Project Owner by the government. The Project Owner returns the tender offers and if the offer is accepted, project permits will be provided in reply to the authorization request of the Project Owner.

The hatched squares (including Governments, Project Owner and External Investors) represent potential investors of the project who should intercommunicate on the funds allocated for the project. There are still several uncertainties about the actors who have to pay for developing CTSC technologies.

External Experts are always engaged to provide expertise usually on technical aspects of the project.

Information on the project has to be shared dynamically with all stakeholders including Local Population, NGOs and Media.

Communication is also essential between governments, NGOs and Local Population, since local communities need to be assured of political support of their policy makers in order to accept CTSC as a novel beneficial technology.

Delays, especially in communication, have to be minimized.

Figure 4.15 underlines the significance of information feedback loops within the safety control structure of CTSC projects. As discussed previously in Chapter 2, information feedbacks allow the actors to improve their mental models, decisions, strategies and decision rules.

Dulac asserts this opinion by remarking that *improving mental models will consequently improve the quality of safety-related decision-making □ and the performance of organizations and systems* [Dulac, 2007; Leveson, 2009]. As previously mentioned, risk acceptance and risk communication are integrated in risk management process [Condor *et al.*, 2011]. Risk communication involves providing information for stakeholders to improve their understanding of the risks related to a phenomena or a technology. Mental models are the schemas of human beings which help them make decisions. Investigating mental models of both experts and lay people provide essential information for communication. [Skarlatidou *et al.*, 2012]

In the next chapter, principal features, advantages and limitations of the methodology will be summarized and suggestions will be provided for further research.

Summary, Chapter 4

In this chapter, application of the methodology for three case studies (Barendrecht, Lacq and Weyburn) was explained. The case studies were selected based on the level of project success. The context of each case study and major challenges related to each project were presented. Safety control structures were developed for each example in order to analyze the factors involved in the success or failure of projects.

Afterwards, the three projects were compared in terms of context and associated risks. Reviewing the context in which these projects were/are working is important since CTSC projects safety control structure is context specific. Furthermore, risks are considered as emergent properties of systems in our approach, which need to be analyzed in their particular context. Project scale, main objective and concerning industry were mentioned as critical parameters that make the projects similar or different. A section was devoted to studying the risks concerning the case studies. Interconnections of the risks were presented in the form of causal graphs. Major (potential) inadequate control actions having the potential to end or ended in delay or failure of projects were discussed. The results were then illustrated in SWOT (Strengths, Weaknesses, Opportunities and Threats) matrices. At the end of the chapter, a generic safety control structure was proposed for CTSC projects, according to the lessons learned from case studies analysis. Emphasis is placed on the importance of information feedback loops and communication between stakeholders, which lead to improve their mental models and decisions.

Résumé (French Summary of Chapter 4)

Ce chapitre présente l’application de la méthodologie sur trois études de cas : Barendrecht (Pay-Bas), Lacq (France) et Weyburn (US). Les études de cas ont été sélectionnées selon le niveau de réussite des projets de CTSC. Le contexte de chaque étude de cas et les défis majeurs liés à chaque projet ont été présentés. Les structures de contrôle de sécurité ont été développées pour chaque exemple, afin d'analyser les facteurs impliqués dans le succès ou l'échec des projets.

Ensuite, les trois projets ont été comparés selon leur contexte et les risques associés. Examiner le contexte dans lequel ces projets ont été préparés et développés est important puisque la structure de contrôle de sécurité des projets de CTSC est spécifique au contexte. Par ailleurs, comme les risques sont considérés en tant que propriétés émergentes des systèmes, il convient de les analyser selon leur propre contexte. L’échelle du projet, son objectif principal et l'industrie concernée ont été mentionnés en tant que paramètres critiques pour les comparer. Une partie de ce chapitre a aussi été consacrée à l'étude des risques concernant ces études de cas. Les interconnexions des risques ont été présentées sous forme des graphes causaux. Les principales actions de contrôle inadéquates ayant entraînées ou ayant le potentiel d’entraîner le retard ou l’échec des projets ont été examinées. Les résultats sont ensuite illustrés sous forme des matrices SWOT (Strengths, Weaknesses, Opportunities and Threats). À la fin du chapitre, une structure générique de contrôle de sécurité a été proposée pour les projets de CTSC, selon les retours d’expérience issus de l’analyse des études de cas. L'accent est mis sur l'importance des boucles de rétroaction d'information et de la communication entre les parties prenantes, qui conduisent à améliorer leurs modèles mentaux et leurs décisions en phase amont des projets de CTSC.

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Chapter 5: Conclusions, Advantages & Limits of the Methodology and Suggestions for Further Studies

5.1 Proposed Methodology: Overview & Advantages

Capture, Transport and Storage of CO_2 (CTSC) is considered as an essential technology for climate change mitigation. However, risks and uncertainties related to long term reliability of the technology have resulted in a kind of uncertain future for CTSC projects development.

CTSC is claimed to play *a new moderating role in opposition to coal* [Stephens, 2012]. Such moderating role is extremely important in the current coal-dependent energy policy. On the other hand, CTSC has been sometimes expressed as a technology that leads to *fossil-fuel lock-in* [Unruh & Carrillo-Hermosilla, 2006; Vergragt *et al.*, 2011]. It is argued that CTSC will not help getting rid of fossil fuels. On the contrary, it could amplify the dependence of energy market on fossil fuels. Stephens believes that CTSC deals with a two-fold lock-in: technical and political. She argues that *for those governments and private companies that have already invested millions or billions of dollars to advance CCS, ending their support for this technology may be difficult even if perceptions of the relative challenges and potential of CCS continues to change over time* [Stephens, 2012].

Koornneef *et al.* have recently identified several knowledge gaps in the field of CTSC environmental and risk assessment, which *may have the potential to postpone the implementation of CCS*. They believe that uncertainties regarding risk assessment could be a *bottleneck for wide scale implementation of CCS if not properly addressed*. In terms of technical risk assessment, Capture and Transport are supposed to be sufficiently understood, although further studies are required to identify potential failure scenarios and their consequences. CO_2 storage is known as a *non-engineered* part of the chain for which quantitative risk assessment is currently impossible [Koornneef *et al.*, 2012]. EU commission has confirmed that uncertainty is a major barrier to invest on low carbon energy systems [EU commission, 2011].

A systemic risk management framework for CTSC projects has been proposed in this work. The approach is founded on the concepts of systems thinking, STAMP, STPA and system dynamics. The objective is to provide a means of decision making for CTSC projects development in the actual context where the future of the technology is uncertain. Risk management is considered as a means of control that should be able to propose a control structure for the whole system. Stakeholders are viewed as controllers of the system. Four conditions are required for the controller [Leveson, 2009]:

- Having a goal
- Being able to affect the system
- Being or contain a model of the system
- Being able to observe the system

Eight Large Scale Integrated CTSC projects have been cancelled in 2011 and 2012 for different reasons especially insufficient or uncertain financial resources, lack of political support and regulatory issues. Projects were cancelled in different countries such as UK, Germany, US, Canada and Australia, and at various stages of development [GCCSI, 2012b]. In 2009, global financial crisis had been identified as a key reason of CTSC projects cancelling or delay [GCCSI, 2009b].

In the previous chapters, actual context of CTSC, theoretical basis of the approach and details of methodology application have been discussed.

Major risks involved in CTSC projects progress have been categorized in eight groups including Technical, HSE (Health, Safety and Environment), Policy/Strategy, Legal, Organizational/Human, Financial/Economic, Social and risks concerning the Project. Thirty nine risks have been identified according to literature review, available projects information and discussions with experts. The risks have been classified for Capture, Transport and Storage subsystems and for different phases of the project. Opportunity, Definition and planning, Engineering, Construction, Operation (Injection of CO_2) and Post-injection (Monitoring) are the main project phases that have been taken into account. In order to analyze the risks preventing project progress, the ones related to the phases prior to engineering have been selected and modeled by the proposed methodology. The aim was to study the feedback networks affecting the risks amplification. The analysis has been started from stock / flow models of each risk. Models have been subsequently grouped together in order to study interconnections of risks and feedback loops result in project failure or success.

Safety control structures of three case studies have been reviewed to find a generic structure that could work for CTSC projects. Inadequate control actions to maintain safety constraints have been discussed. The idea comes from STAMP and STPA approaches, developed at MIT. The proposed safety control structure has been presented in chapter 4, following comparison of the case studies in terms of context and associated risks. The purpose was to underline the significance of endogenous point of view in analyzing the risks of CTSC projects. It has been argued that feedbacks and feedback loops have to be understood and studied in the networks of risks and stakeholders. Emphasis is placed on the importance of providing endogenous explanations for CTSC actual development context. As discussed earlier in chapter 2, it is more favorable to have endogenous perceptions about all phenomena.

CTSC risk management is context specific and depends on several factors such as national and local circumstances. In spite of that, seeking for individual benefits is indeed a major concern of all stakeholders. Oil and gas industry is currently more involved in the field by investing on CTSC EOR projects. Oil recovery increase is the main obvious advantage of EOR systems.

Lessons learned from the modeling process of this work show that dynamic information sharing and communication are essential to support the contribution of CTSC technologies in climate change mitigation.

The thesis contribution provides a decision making support for the progress of CTSC projects. Systemic modeling of CTSC project risks can help the stakeholders to share and improve their mental models and accordingly, their strategies and decisions.

In order to give a summary of the proposed methodology advantages, we have to go back to available CTSC risk management approaches. As discussed in chapter 1, several works have been already performed on risk management of CTSC. Most of these works are focused on one part of the chain, i.e. Capture, Transport or Storage; and especially on technical aspects of risk. However, in chapter 1 we introduced some integrated approaches of CTSC risk management. INERIS, National Institute of Industrial Environment and Risks in France, proposes a global risk analysis approach for CTSC chain. They propose to integrate the notion of time to the classic concepts of probability and severity for CTSC risk analysis. Three time scales are suggested: operation (max. 50 years), monitoring (max. 150-200 years) and long term (up to 1000 years). Different aspects of risks are not included in the approach of INERIS. Their study is focused on technical risk scenarios related to storage [Farret *et al.*, 2009]. Therefore, in subsequent paragraphs we will review the main characteristics of two available integrated approaches for the purpose of better understanding the values of our proposed systemic methodology.

GCCSI has presented a qualitative risk assessment methodology which has been developed based on AS/NZS 4360: 2004 (Australian and New Zealand standard for risk management). Seventeen *extreme* risks have been identified by an expert panel, and classified in four main categories: Public, Business Case, Governmental/Regulatory/Policy and Technical. Consequences and likelihood of each risk have been then specified by the expert panel. An example of the identified risks is available in Figure 5.1.

Risk Description (Event and Consequence)	Category	Existing Controls	Consequence		Likelihood	
Public opposition leads to a lack of political will to support CCS.	Public	Limited education of stakeholders (public and policy makers) that CCS must be deployed to mitigate climate change.	4	Major	A	Almost Certain
Global financial crisis leads to inability to secure private sector finance of CCS projects.	Business Case	Economic stimulus packages provided by governments. Direct funding mechanisms proposed by Canadian, European, US and Australian Governments.	4	Major	A	Almost Certain
A lack of detailed knowledge of site specific trapping mechanisms leads to greater uncertainty in predictive modelling for early projects resulting in prolonged and costly planning stages.	Technology - Sequestration	Some small-scale injection testing and use of analogue set from other relevant geologic formations.	4	Major	A	Almost Certain
A lack of fundamental knowledge of geology in many regions of the world leads to uncertainty on the number and size of potential storage reservoirs. Limited ability to launch integrated CCS projects on a global basis.	Technology - Sequestration	Some geological surveys being initiated.	4	Major	A	Almost Certain
Public opposition arising from perceptions of catastrophic leakage (pipelines and storage) leads to project delays or cancellations.	Public	Limited education campaigns to inform stakeholders that CCS is integral to mitigate threat of climate change. Leverage off hydrocarbons experience and educate on relative risk of storage.	4	Major	A	Almost Certain

Figure 5.1: Example of extreme risks identified by [GCCSI, 2009a]

In the first column of Figure 5.1 the risk is described. The category and existing controls are specified in the second and third columns. Consequences and likelihood related to each risk are provided at the end. For example “Public opposition leads to a lack of political will to support CCS” is considered in “Public” category. The control which is mentioned in Figure 5.1 is the availability of some education programs for stakeholders, including public and policy makers, to accept CTSC as a climate change mitigation option.

The figure in between “Existing controls” and “Consequence” columns refers to the level of risk, which is defined based on the degree of consequences and likelihood.

Number “4” represents an “*extreme*” risk. The risk matrix used by [GCCSI, 2009a] is presented in Figure 5.2.

			Consequence				
			Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	A	Almost Certain	High	High	Extreme	Extreme	Extreme
	B	Likely	Moderate	High	High	Extreme	Extreme
	C	Moderate	Low	Moderate	High	Extreme	Extreme
	D	Unlikely	Low	Low	Moderate	High	Extreme
	E	Rare	Low	Low	Moderate	High	High

Figure 5.2: Risk Matrix used by [GCCSI, 2009a]

GCCSI asserts that *many of these risks are complex, inter-related and dynamic* [GCCSI, 2009a]. Nevertheless, the complexity, interrelations and dynamic characteristic of risks have not been studied by GCCSI. Therefore, the advantage of the current thesis proposed methodology compared with GCCSI approach is that our proposed systemic methodology provides a modeling framework for analyzing the complex interrelation network of risks associated to CTSC projects. In addition to [GCCSI, 2009a], a number of recent references have been used to determine the risk categories of the present work (Table 3.3). Consequently, our risk categories are more comprehensive than the ones presented by GCCSI.

Another integrated risk assessment approach has been proposed by [Kerlero de Rosbo, 2009] for Belchatow project in Poland. Risks have been sorted out in five main groups: Technical, Financial, Organization & Management, Social & Political, and Regulatory. A semi-quantitative approach has been applied by [Kerlero de Rosbo, 2009]. The methodology steps are indeed same as a classic risk management process, including analysis, evaluation and treatment of risks (refer to Figure 1.13 for the process of risk management). The methodology is illustrated in Figure 5.3:

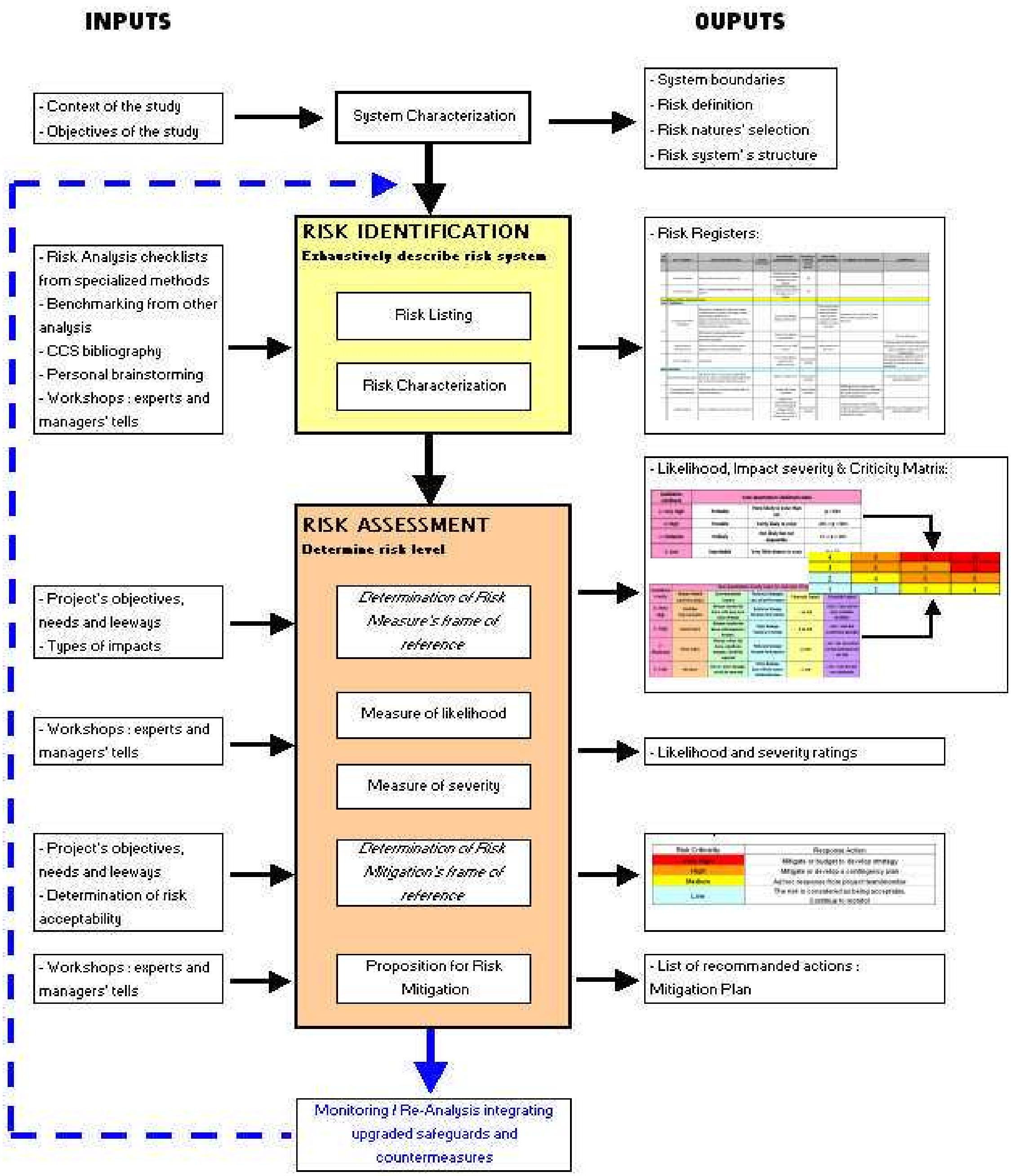

Figure 5.3: Integrated CTSC Risk Management methodology proposed by [Kerlero de Rosbo, 2009]

Risks as well as their likelihood and severity have been identified in expert panels. Although several aspects of risk have been included in Kerlero's methodology, interconnections of risks are not analyzed in his approach.

In addition to risk interrelations, another point which seems to be necessary to be integrated in CTSC risk management processes is the importance of stakeholders role in the project success or failure. The significance of safety control structure (as defined in chapter 3) has not been taken into account in the integrated methods of [GCCSI, 2009a] and [Kerlero de Rosbo, 2009]. Responsibilities of different stakeholders of CTSC project is what we have highlighted in our systemic approach. Each stakeholder is considered as a controller who has to maintain specific safety constraints in order to fulfill the objective of safety structure, i.e. preventing delay or failure of CTSC project. In the current thesis, defects of safety control structure have been noted as major potential cause of a CTSC project failure (refer to Barendrecht project analysis, section 4.1.1).

To sum up, three advantages can be listed for the systemic methodology which is proposed in this thesis:

- Presenting more comprehensive list and categories of risks related to CTSC chain
- Taking into account the complex network of risk interconnections by proposing a systemic modeling framework
- Underlining the significance of stakeholders role in the project success or failure, by proposing a modeling approach for safety control structure of projects and analyzing required and (potential) inadequate control actions of stakeholders in relation to each risk

The systemic methodology proposed in this thesis has some limitations in spite of its advantages and added values. Limitations are classified in three groups presented hereafter.

5.2 (Potential) Limitations of the proposed methodology

5.2.1 Lack of information on CTSC

Refer to the discussions of chapter 3, CTSC integrated chain is an emerging technology for which there is not a great amount of publicly available information [CCP, 2007]. Details of case studies are usually unavailable due to confidentiality issues. Nevertheless, the methodology has been applied for three case studies on the basis of accessible data in the literature, project reports and discussions with experts. The analysis could be improved based upon lessons learned from further development of projects.

5.2.2 Qualitative vs. quantitative approach

A qualitative approach was proposed in this thesis for risk management of CTSC. It may be debated that quantitative methods are more practical or more comprehensible. In this section, the notion of quantification is reviewed from three points of view: risk quantification, quantification in STAMP approach, and system dynamics quantitative modeling.

As mentioned earlier in chapter 1, *operators and public organizations have initially tried to quantify damages and consequences of potential accidents, before to understand why and how they could occur* [Tixier *et al.*, 2002]. From another standpoint, quantitative approaches are not necessarily the most adapted ones for modern complex sociotechnical systems [Dulac, 2007, p.29]. Altenbach mentions ten reasons for which risks should not be quantified. Controversiality, potential use of numbers out of context, simplification of numbers for challenge and criticism, being *time consuming and costly*, *uncertainties*, requirement of *more training*, *data* requirement, being *threatening and compelling*, usefulness of qualitative results and difficulty to *communicate the concept of probability* are noted as the reasons not to quantify risks [Altenbach, 1995].

The proposed methodology is based on STAMP approach, which has been mostly used as a qualitative tool to analyze accidents or risks. Dulac affirms that *quantitative values generated in the simulations are sometimes of secondary importance in comparison to the qualitative learning opportunities presented by the model and the modeling process* [Dulac, 2007, p.213]. The significance of modeling process is also attested by [Durand, 2010].

From system dynamics point of view, qualitative or *soft* applications of stock-flow and / or causal diagrams are recognized as useful as simulation applications. Qualitative use allows developing feedback networks and understanding the system behavior [Winch, 2000].

Hence, being qualitative is not a limitation of the proposed methodology. As Coyle suggests, we should wonder *how much value does quantified modeling* in system dynamics *add to qualitative analysis* [Coyle, 2000].

5.2.3 Subjectivity of modeling and risk assessment

Modeling, which is a simplification of reality, is made by an individual or a group of individuals. As a result, modeling is always a subjective process, depending on the reasoning of modeler(s). The models developed in this thesis are not an exception. They have been created based on the mental models of the modeler, which are inevitably restricted. According to Durand, modeling is an art and not an established technique [Durand, 2010, p.68]. Models of the current thesis are made by only one modeler and have not been verified by an expert panel. Group modeling provides different points of view to improve the models.
In addition, risk assessment is a subjective process since expert judgment is an indispensable characteristic of risk assessment process.

5.3 Suggestions for further studies

CTSC risk management deals with several gaps and issues, and therefore requires more research. Further studies could be carried out on the subjects already introduced as limitations of the methodology.
Development of CTSC projects will provide lessons learned for improving the models. New information could be used to put figures on the variables of models in group modeling panels. Figures help to make semi-quantitative analyses which may be more understandable for some stakeholders. Effects of feedback loop networks on the probability and intensity of risks could be studied in semi-quantitative approaches.
Financial/Economic aspects have to be developed in detail in further studies. Significance of CO_2 monetary systems such as EU ETS (European Union Emissions Trading System) needs to be analyzed thoroughly.
Models and control structures of chapters 3 and 4 provide an appropriate basis for stakeholder discussion panels. Different failure scenarios in the developed feedback network models could be envisaged and studied in the discussion panels. Cumulative effects of failures are recommended to be studied by thinking about cumulative consequences of risks, as stock variables of the models. Modeling could be a learning and communication tool for operators, managers and all the actors engaged in the prevention and management of risk [Garbolino *et al.*, 2010]. Copin confirms that

dynamic modeling could be a tool for training the actors in the organization, particularly managers. Application of software, such as STELLA® or VENSIM®, makes it easier to train the actors and help them to make required decisions [Copin, 2000].

The proposed modeling framework could be served to study the performance of CTSC within a comprehensive framework. Current main aspects of CTSC performance include:

- Economic performance:

  Economic performance is an essential aspect of CTSC performance. As noted in previous chapters, high cost of capture processes is a major concern. Capital cost of the plant with and without CO_2 capture and cost of electricity production with and without CO_2 capture are some of the critical economic performance indicators [Rubin *et al.*, 2007].

- Technical performance:

  Technical performance of CTSC technologies has various facets including energetic and environmental.

  As discussed earlier and at the beginning of the current chapter, CTSC is still principally dependent on fossil fuels while it is supposed to be a technological option to reduce fossil fuel-based CO_2 emissions. Hence, further studies are required on energetic performance of CTSC.

  CTSC environmental performance has to be analyzed according to CO_2 emission factors with and without capture process.

  Details of technical performance indicators are not in the scope of this thesis. More information is available in several references such as [Koornneef *et al.*, 2012; Rubin *et al.*, 2007].

- Organizational performance:

  As previously argued, CTSC is a complex sociotechnical system in which several public and private organizations are engaged as stakeholders. Managing risks and uncertainties needs an interactive communication of stakeholders. Organizational performance plays a significant role in sustainability of CTSC projects implementation.

The risks reviewed and modeled in the present work cover all these aspects of performance. Consequently, the proposed methodology is helpful in performance analysis of CTSC projects.

Each of the risks presented in Table 3.1 could be considered as a performance indicator of CTSC project. Lorino defines performance as all the elements that contribute to meet the strategic objectives [Lorino, 2003, p.9]. Performance could be measured by performance indicators. According to Fernandez, "indicator" is an information or a group of information contributing to evaluate a situation by a decision maker [Fernandez, 2010, p.263]. Performance indicator is a piece of information that should help an actor, an individual or a group to carry out the activities in order to meet the objectives, or evaluate the results [Lorino, 2003, p.130].

A scorecard ("tableau de bord" in French) might be created by using the performance indicators. Fernandez [Fernandez, 2010, pp.4 & 35] defines the scorecard as:

- An instrument for measurement of performance, that is necessary for all the actors of the company to make decisions or
- An instrument of sharing the decision-making information for having access to the global knowledge

He states that scorecard has various functions. A scorecard could be used for communication or sharing information with the stakeholders. It could be a personal tool to take an action or make a decision, a tool to define the dysfunctions of the system, or even for anticipation of the future state of the system [Fernandez, 2010, p.259]. This idea is illustrated in Figure 5.4.

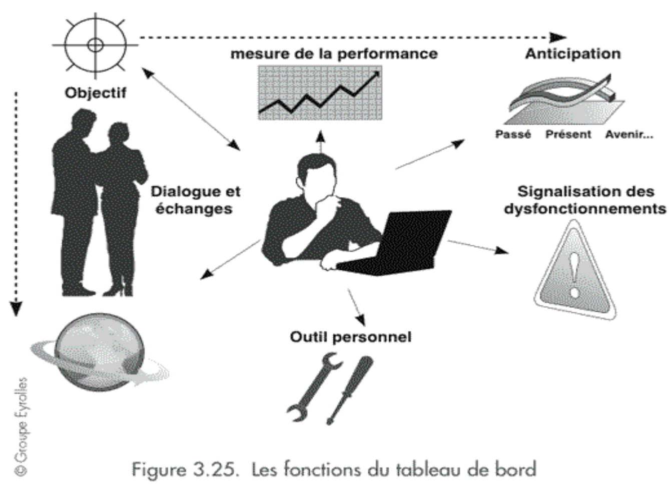

Figure 5.4: Functions of a scorecard [Fernandez, 2010]

The works of Kaplan and Norton might be helpful in terms of performance from company manager s point of view. They believe that *executives want a balanced presentation of measures that allow them to view the company from several perspectives simultaneously*. They have developed a *new performance measurement system,* called "*balanced scorecard*", to give top managers a *comprehensive view of the business*. The balanced scorecard covers not only financial measures but also three groups of operational measures including *customer satisfaction, internal processes, and the organization's ability to learn and improve* [Kaplan & Norton, 1992]. Each of the risk categories previously presented for CTSC (Table 3.3) could be included in the first or third operational measures of Kaplan and Norton (*customer satisfaction* or *the organization's ability to learn and improve*). Technical, Project, HSE and Organizational/Human risks are the most relevant issues that could be considered in *internal processes* category of Kaplan and Norton measures.

The risks that have been presented in the current work could provide information for creating a scorecard of control and monitoring CTSC project performance. As previously discussed, one of the concerns is that most of the risks presented in Table 3.1 are complex issues which are still under study. Hence, acquiring information to quantify performance indicators will be a challenge, which needs the contribution of experts from different fields while CTSC projects are developing.

Another issue that needs to be improved is the concept of delay, already introduced and reviewed in this work. Additional study on potential decision making delays and their consequences on the project progress will be valuable.

The methodology and developed models could not be verified due to lack of time. Further work is recommended to evaluate and enhance the models, with the assistance of stakeholders, especially project owners. Participation of a group of CTSC and system dynamics experts will be useful in the evaluation process. The methodology is suggested to be applied for a CTSC project in feasibility study or definition phase.

Summary, Chapter 5

In chapter 5, the most significant points of the context and the proposed methodology were wrapped up. It was discussed that CTSC deals with two kind of lock-ins: technical and political. Technical lock-in involves the notion of fossil fuel lock-in, and the fact that CTSC technologies extremely depend upon fossil fuel consumption. This situation is claimed as being contrary to CTSC contribution in climate change mitigation. Such ambiguous position along with uncertainties concerning risk assessment could be a barrier for investing on large scale CTSC projects.

The methodology which is proposed in the current thesis provides a means of decision making for CTSC projects development. The methodology was compared with two available integrated CTSC risk management approaches. The major advantages include: more comprehensive list and categories of risks, taking into account the complex network of risk interconnections, and highlighting the significance of stakeholders role in the project success or failure.

(Potential) Limitations of the methodology were presented in section 2. Lack of information on CTSC, debate on the requirement of quantitative or qualitative risk management approaches, and subjectivity of modeling and risk assessment are the most important limitations of the current work. Some suggestions for future research were provided at the final section. It was argued that the proposed methodology can be useful in studying the general performance of CTSC from economic, technical and organizational points of view. In addition, the presented risks could be considered as performance indicators of CTSC projects, which could provide information for creating a scorecard.

Résumé (French Summary of Chapter 5)

Le chapitre 5 résume les points les plus importants du contexte et de la méthodologie proposée. La technologie de CTSC est enferrée dans un double contexte technique et politique. Le blocage technique implique la dépendance du CTSC face à la consommation de combustibles fossiles. Cette situation est considérée comme contraire à la contribution du CTSC pour atténuer le changement climatique. Avec une telle position ambiguë ainsi que des incertitudes concernant l'évaluation des risques, les projets de CTSC à grande échelle rencontrent des difficultés pour leur développement.

La méthodologie qui est proposée dans cette thèse fournit un moyen de prise de décision pour développement des projets de CTSC. La méthodologie a été comparée avec deux approches intégrées qui sont disponibles pour le management des risques du CTSC. Les avantages majeurs comprennent : une liste et des catégories plus complètes des risques, la pris en compte de réseau complexe des interconnexions entre les différents risques, et la mise en évidence de l’importance du rôle des parties prenantes pour le succès ou l’échec du projet. Nous avons donc proposé que notre méthodologie puisse être utile à l’étude de la performance générale du CTSC du point de vue économique, technique et organisationnel.

Les Limites potentielles de la méthodologie ont été présentées dans la deuxième partie du chapitre. Le manque d'informations sur le CSTC, le débat sur l'exigence des approches quantitatives ou qualitatives de gestion des risques, et la subjectivité de la modélisation et de l'évaluation des risques constituent les principales limites de ce travail. Quelques suggestions ont été fournies dans la partie finale pour les perspectives de recherches. Parmi elles, le recours à l’intégration d’indicateurs de performance en risk management dans des tableaux de bord constituerait un moyen dédié aux parties prenantes pour accompagner le développement et le suivi des projets de CTSC.

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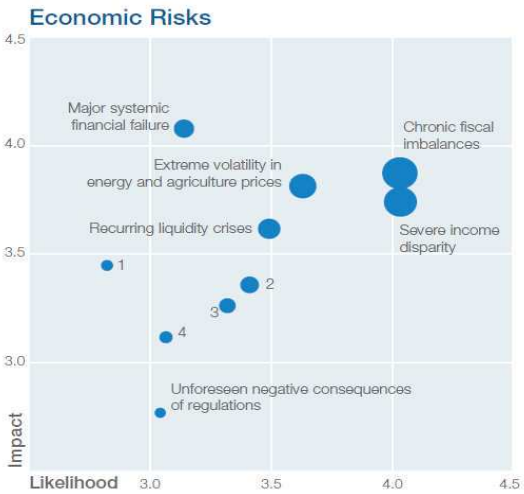
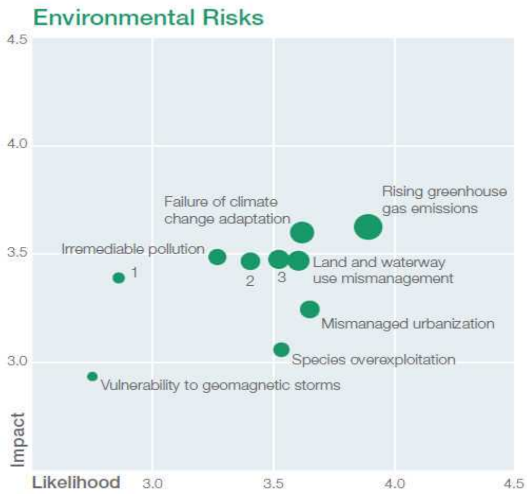
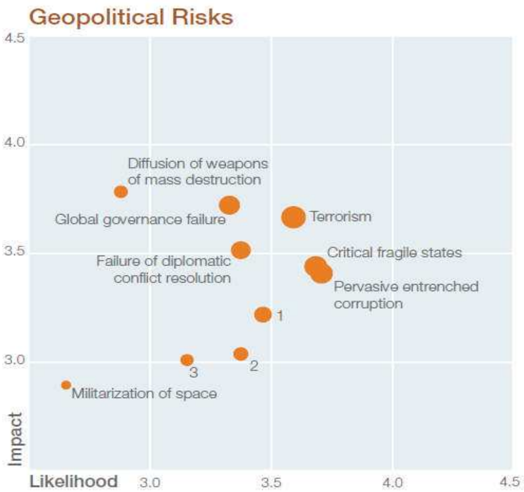
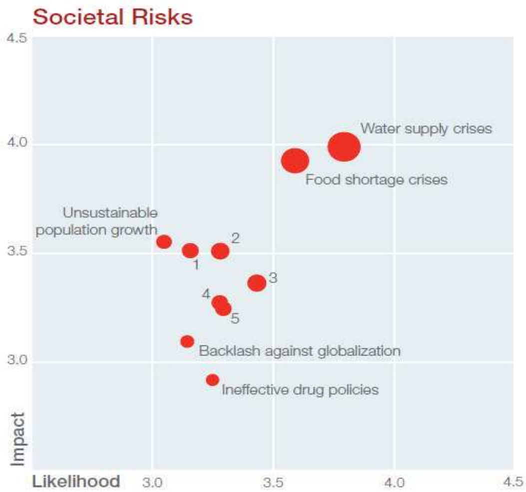
Appendixes

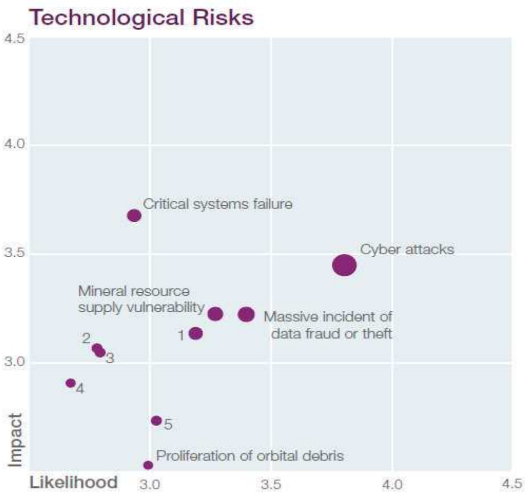
Appendix 1: Five Global Risks Categories [WEF, 2012]











1. Unmanageable inflation or deflation
2. Chronic labour market imbalances
3. Prolonged infrastructure neglect
4. Hard landing of an emerging economy

1. Unprecedented geophysical destruction
2. Persistent extreme weather
3. Antibiotic-resistant bacteria

1. Entrenched organized crime
2. Widespread illicit trade
3. Unilateral resource nationalization

1. Vulnerability to pandemics
2. Rising religious fanaticism
3. Mismanagement of population aging
4. Unmanaged migration
5. Rising rates of chronic disease

1. Massive digital misinformation
2. Unintended consequences of new life science technologies
3. Unintended consequences of climate change mitigation
4. Unintended consequences of nanotechnology
5. Failure of intellectual property regime

Appendix 2: Global Risks Landscape 2012 [WEF, 2012]

Appendix 3: Sources of industrial CO2 emissions of more than 0.1 MtCO2 per year [IPCC, 2005]

Process	Number of sources	Emissions ($MtCO_2\ yr^{-1}$)
Fossil fuels		
Power	4,942	10,539
Cement production	1,175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	**7,887**	**13,466**

Appendix 4: Published exposure limits to CO_2 [Johnsen *et al.*, 2009]

Exposure Time	% CO_2	Comment	Reference
10 hours	0.50%	Time weighted average	NIOSH (US)
8 hours	0.50%	Time weighted average	OSHA (US)
8 hours	0.50%	Occupational Long Term Exposure Limit (LTEL)	COSHH HSE (UK)
60 mins	4%	Emergency Exposure Level for submarine operations	USA Navy
	2.5%	Emergency Exposure Level for submarine operations	National (US) Research Council
	5%	Suggested Long Term Survivability Exposure Limit	HSE (UK)
	2%	Maximum exposure limit	Compressed Gas Association 1990
20 mins	3%	Maximum exposure limit	Compressed Gas Association 1990
15 mins	1.5%	Occupational Short Term Exposure Limit (STEL)	COSHH HSE (UK)
	3%	Short Term Exposure Limit (STEL)	Federal occupational safety and health regulations (US)
10 mins	4%	Maximum exposure limit	Compressed Gas Association 1990
7 mins	5%	Maximum exposure limit	Compressed Gas Association 1990
5 mins	5%	Suggested Short Term Exposure Limit (STEL)	HSE (UK)
	6%	Maximum exposure limit	Compressed Gas Association 1990
3 mins	7%	Maximum exposure limit	Compressed Gas Association 1990
1 min	15%	Exposure limit	NORSOK (Norway)
<1 min	4%	Maximum Occupational Exposure Limit	Federal occupational safety and health regulations (US)

Appendix 5: Areas of concern of different CTSC stakeholders [CCP, 2012]

	EHS Impacts	Awareness & acceptance of CCS	Technical aspects	Commercial & local development benefits	Policy & legal issues	Diversion from renewable energy	Positive impact on climate change	Variable positions on CCS
NGOs & Thought Leaders	✓		✓		✔	✔	✔	✔
General Public	✓	✓	✓	✓	✔	✔	✔	
Politicians & Policy makers	✓	✓	✓	✓	✔	✔	✔	✔
Industry	✓		✔	✔	✔	✓	✓	
Local Community	✔	✓	✓	✔	✓			✓
Regulators	✔	✔	✔		✓			
Investors	✓	✓		✔	✔			
Media	✓	✓	✓	✓	✓	✓	✓	✓

✔ Focus of interest ✓ Issue noted

Glossary

atm.	:	Atmosphere (pressure unit of measurement)
ALARP	:	As Low As Reasonably Practicable
Ar	:	Argon
AS/NZS 4360: 2004	:	Australian/New Zealand risk management standard, version 2004
bar	:	Pressure unit of measurement
bara	:	Bar absolute (pressure unit of measurement)
BARPI	:	Bureau d'Analyse des Risques et Pollutions Industriels
BCO_2	:	Bestuurlijk overleg CO_2, Administrative consultation group of Barendrecht project
BLEVE	:	Boiling Liquid Expanding Vapor Explosion
BRGM	:	Bureau de Recherches Géologiques et Minières
°C	:	Degrees of Celsius (temperature unit of measurement)
CA	:	Competent Authorities
CCJ	:	Carbon Capture Journal
CCP	:	CO_2 Capture Project
CCR	:	Carbon Capture Readiness
CCS	:	CO_2 Capture and Storage
CH_4	:	Methane
CL_2	:	Chlorine
CLIS	:	Commission Locale d'Information et de Suivi
CO	:	Carbon monoxide
CO_2	:	Carbon dioxide
CTSC	:	Capture, Transport and Storage of CO_2
DCMR	:	Dienst Centraal Milieubeheer Rijnmond, Environmental protection agency of Rinjmond in the Netherlands
DEA	:	Di Ethanol Amine

DECC	:	Department of Energy and Climate Change
DNV	:	Det Norske Veritas
DRIRE	:	Direction Régionale de l'Industrie, de la Recherche et de l'Environnement
ECBM	:	Enhanced Coal Bed Methane recovery
EIA	:	Environmental Impact Assessment
EOR	:	Enhanced Oil Recovery
ESD	:	Emergency Shut Down
EU	:	European Union
EZ	:	The Netherlands Ministry of Economic Affairs
FEED	:	Front End Engineering Design
FEP	:	Features, Events, Processes
FMEA	:	Failure Modes and Effect Analysis
FMECA	:	Failure Modes and Effect Criticality Analysis
FTA	:	Fault Tree Analysis
GCCSI	:	Global CO_2 Capture and Storage Institute
GESIP	:	Groupe d'Etudes de Sécurité des Industries Pétroliers et chimiques
GHG	:	Green House Gas
Gt	:	Giga (10^{12}) tonnes
H_2	:	Hydrogen
H_2O	:	Water
H_2S	:	Hydrogen Sulfide
HAZOP	:	HAZard and OPerability study
HSE	:	Health, Safety and Environment
ICPE	:	Installation Classée pour la Protection de l'Environnement
IEA	:	International Energy Agency

IEC 60300-3-9:1995	:	International Electrotechnical Commission standard for risk management. Guide to risk analysis of technological systems, version 1995
INERIS	:	Institut National de l'Environnement Industriel et des Risques
IPCC	:	Intergovernmental Panel on Climate Change
IPPC	:	Integrated Pollution Prevention and Control
IRGC	:	International Risk Governance Council
ISO/IEC 73: 2002	:	International standard for risk management – Vocabulary – Guidelines for use in standards, version 2002
km	:	Kilometer
km^2	:	Square kilometer
LNG	:	Liquified Natural Gas
LSIP	:	Large Scale Integrated Project
m	:	meter
max.	:	maximum
MDEA	:	Methyl Di Ethanol Amine
MEA	:	Mono Ethanol Amine
MIT	:	Massachusetts Institute of Technology
Mt	:	Million (10^6) tonnes
Mtpa	:	Million tonnes per annum
MW	:	Molecular Weight
N_2	:	Nitrogen
NAM	:	Netherlandse Aardolie Maatschappij BV, the Netherlands biggest oil and natural gas producer
NASA	:	US National Aeronautics and Space Administration
NGO	:	Non Governmental Organization
NO	:	Nitrogen mono-oxide
NO_2	:	Nitrogen di-oxide
NO_x	:	Nitrogen Oxides (NO or NO_2)

O_2	:	Oxygen
OCAP	:	Organic CO_2 for Assimilation of Plants, Shell's joint venture for CO_2 transport in Barendrecht project
OECD	:	Organization for Economic Co-operation and Development
ppm	:	Parts per million
PRA	:	Probabilistic Risk Assessment
PTRC	:	Petroleum Technology Research Center
QRA	:	Quantitative Risk Assessment
R&D	:	Research & Development
SO_2	:	Sulfur dioxide
SO_3	:	Sulfur trioxide
SO_x	:	Sulfur Oxides (SO_2 or SO_3)
STAMP	:	Systems-Theoretic Accident Model and Processes
STEL	:	Short Term Exposure Limit
STPA	:	Systems-Theoretic Process Analysis
SWOT	:	Strengths, Weaknesses, Opportunities and Threats
t	:	tonnes
UK	:	United Kingdom
UNFCCC	:	United Nations Framework Convention on Climate Change
US	:	United States of America
US$	:	United States dolor
vol%	:	Volume percent
VROM	:	The Netherlands Ministry of Housing, Spatial Planning and Environment
WEF	:	World Economic Forum

Développement d’une approche systémique de management des risques pour les projets de CTSC

RESUME : Cette thèse concerne l’étude des risques associés aux projets de CTSC (Captage, Transport et Stockage de CO_2) dont le développement est prévu à l’échelle industrielle. Les projets de CTSC sont des systèmes sociotechniques complexes pour lesquels une approche systémique de management des risques est nécessaire. L’approche doit couvrir les différents aspects du risque pour analyser l’influence de la dynamique des risques sur la dynamique des projets. Une méthodologie systémique de management des risques est proposée. Cette méthodologie est fondée sur les concepts de la pensée systémique, de l’approche STAMP (Systems-Theoretic Accident Model and Processes) développée au sein du Massachusetts Institute of Technology, et de la dynamique des systèmes. L'objectif est de modéliser et d'analyser la structure de contrôle de sécurité impliquée dans un projet de CTSC. La structure de contrôle de sécurité est la structure organisationnelle des parties prenantes (contrôleurs) qui sont responsables de maintenir les contraintes de la sécurité. L'objectif de cette structure de contrôle de sécurité dans cette thèse est d’éviter le retard ou l’échec des projets de CTSC. Cet objectif a été reformulé comme étant la définition et le management des risques majeurs qui pourraient empêcher ou limiter le maintien des contraintes de sécurité. Les risques ont été d’abord identifiés et classés selon huit catégories : Technique, SSE (Santé, Sécurité et Environnement), Politique/Stratégie, Réglementation, Organisationnel/Humain, Financier/Economique, Social et Projet. Les risques majeurs liés aux phases amont ont été extraits et modélisés en utilisant la méthodologie proposée. Les rétroactions affectant la propagation et l'amplification de chaque risque ont été étudiées. Les structures de contrôle de sécurité, le contexte et les risques associés des projets de Barendrecht, de Lacq et de Weyburn ont été analysés. L’application de la méthodologie sur ces trois retours d’expériences permet de proposer un modèle générique de contrôle de sécurité pour les projets de CTSC. L'accent est mis sur le rôle majeur des facteurs endogènes conduisant à l’échec des projets de CTSC. Ce modèle met en évidence les flux d'information et de communication entre les parties prenantes qui conduisent à améliorer leurs modèles mentaux et leurs décisions.

Mots clés : CTSC (Captage, Transport et Stockage de CO_2), Management des Risques, Systémique, STAMP, Dynamique des Systèmes, Modélisation, Structure de Contrôle de Sécurité

Development of a Systemic Risk Management Approach for CTSC Projects

ABSTRACT: This thesis is concerned with understanding the risks associated with the development of CTSC (Capture, Transport & Storage of CO_2) projects up to industrial scales. CTSC projects are complex sociotechnical systems for which a systemic risk management approach is required. The approach has to cover different aspects of risk in order to analyze how dynamics of risks affect dynamics of projects. A systemic risk management framework is proposed based on the concepts of systems thinking, STAMP (Systems-Theoretic Accident Model and Processes), developed at the Massachusetts Institute of Technology, and system dynamics. The objective is to model and analyze the safety control structure involved in a CTSC project. Safety control structure is the organizational structure of stakeholders (controllers) who are responsible for maintaining safety constraints. The goal of safety control structure in this work is to prevent CTSC project delay or failure. This goal has been rephrased as definition and treatment of major risks that could avoid maintaining safety constraints. The risks have been firstly identified and classified in eight main categories including Technical, HSE (Health, Safety and Environment), Policy/Strategy, Legal, Organizational/Human, Financial/Economic, Social and Project. The major risks related to the phases prior to engineering have been extracted and modeled by the proposed methodology. Feedback networks affecting the amplification of each risk have been studied. Safety control structures, context and associated risks of Barendrecht, Lacq and Weyburn projects have been analyzed in order to propose a generic safety control model for CTSC projects. Emphasis is placed on the significance of finding endogenous explanations for the failure of CTSC projects. The model highlights the flow of information and communication among stakeholders leading to improve their mental models and decisions.

Keywords: CTSC (Capture, Transport and Storage of CO_2), Risk Management, Systemic, STAMP, System Dynamics, Modeling, Safety Control Structure

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