A new dynamic risk analysis framework for CO_2 Capture, Transport and Storage chain

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Abstract

CO_2 emission of industrial facilities is a major cause of climate change that affects the ecosystems, human beings and environment. Capture, Transport and Storage of CO_2 (CTSC) is a novel technology of mitigating the impacts of climate change. The uncertainties concerning long term reliability of CTSC technology give rise to the significance of risk assessment for CTSC activities.
Since CTSC is a complex sociotechnical system, traditional risk assessment approaches are not appropriate for CTSC. Lessons learned of industrial accidents show that a combination of technical, organizational and human aspects of risk results in occurrence of accidents. Therefore, we recommend to develop an integrated risk analysis framework for CTSC chain. The framework is developed by modeling CTSC chain by system dynamics approach. System dynamics is a support for risk assessment that allows understanding the interactions of CTSC system's elements in the first step, and then study the behavior of the system over time both in normal operation mode and in case of a failure or deviance.
In this paper, the methodology is explained in detail, and the application of the methodology for an integrated CTSC project is discussed.

Key Words: CO_2 Capture, Transport and Storage, Risk Assessment, System Dynamics, Model, Safety Control System, Climate Change

In this article, a methodology is proposed to develop a dynamic risk analysis framework for Capture, Transport and Storage of CO_2 (CTSC). CTSC is an emergent technology of mitigating CO_2 emissions in the atmosphere and climate change impacts. Nevertheless, risk assessment is a fundamental issue for sustainability of CTSC technology. Our proposed methodology is to model CTSC system by system dynamics approach, and then integrate system dynamics with risk analysis results in order to analyze the behavior of the system in case of a failure or a deviation from normal operation. The paper contains four sections. In the first section, we introduce CTSC system and how it contributes to mitigate climate change impacts. Afterwards, we discuss why a new risk analysis framework is required for CTSC, and why system dynamics approach is appropriate for analyzing risks associated with CTSC system. Then, we review some of the available risk analysis approaches that are based on systems thinking and system dynamics. The third section is devoted to our methodology and applying the approach for a case study. The paper wraps up with a summary of conclusions and future work.

1. Climate change and CTSC

1.1. CTSC contribution to climate change

Climate change is a major environmental concern of our time, affecting ecosystems, food productivity, coast lines, water availability and human beings' health. CO_2 emission to atmosphere is the most significant anthropogenic reason of climate change. According to Intergovernmental Panel on Climate Change (IPCC) [1], several methods are available to avoid, reduce or control the emission of CO_2 to atmosphere. CTSC is one of these options leading to 19% of emissions' reduction by 2050 (GCCSI, 2009). Improvement of energy efficiency, renewable sources of energy, and switch to less carbon-intensive fuels are some of the other possibilities to mitigate climate change (IPCC, 2005). Different countries choose the appropriate mitigation options based on their resources and their policies.

The ultimate goal of CTSC is to store the emitted CO_2 of industrial plants in geological formations or oceans for long periods of time (hundreds or thousands of years). Therefore, studying the potential risks of CTSC is necessary to ensure that CTSC will not have an adverse impact on the environment and on human beings' health, and to be assured of the sustainability of CTSC. The leakage of the stored CO_2 to the water resources may change the acidity of water, and affect the flora and fauna, and even the human beings when the water resource is a potable one. Large releases of CO_2 to the atmosphere from the storage location will result in the exposure of humans and other living species to the CO_2. The risks of exposure to CO_2 depend on the concentration of the released CO_2 and duration of exposure.

In the following paragraphs, we present a brief introduction of CTSC technology before discussing CTSC risk assessment.

1.2. CTSC technology, a brief introduction

CTSC is an emergent technology that refers to a 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.

Combustion of fossil fuels such as coal, oil and gas in power plants, automobiles and industrial facilities is the most significant source of CO_2 emissions. Mineral and metal production processes, such as cement, lime, iron, steel and aluminum production, can also lead to CO_2 emissions (EPA, 2010).

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[1] *IPCC is the leading body for the assessment of climate change, established by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences (IPCC website).*

Several processes are available for Capture, Transport and Storage of CO_2. We provide a brief introduction of each process in the following paragraphs.

Three main processes are available for CO_2 capture:
- Postcombustion: is a chemical or physical process where CO_2 is separated from the flue gases produced by the combustion of fossil fuels (coal, oil or natural gas) or biomass.
- Oxycombustion: is a process where oxygen is used for the combustion of fuel, instead of air. The result is a flue gas with high CO_2 concentration.
- Precombustion: is the process of transforming the fuel to a mixture of carbon monoxide and hydrogen (Synthesis Gas), and then producing 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.

After capturing, CO_2 is transported to the storage location.
CO_2 can be transported either by onshore/offshore pipelines, by tankers or by ships. CO_2 is in supercritical state while transporting by pipeline, 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 condition is the highest temperature and pressure at which gas and liquid phases are at equilibrium. When CO_2 is in supercritical state, it behaves like a gas, but its density is close to the liquid density. Critical temperature and pressure of CO_2 are 31.1°C and 73.9 bar respectively). 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 is transported by ship in liquid phase (20 bar and -20°C) (Lecomte *et al.*, 2010). Transporting CO2 by road and rail tankers is technically feasible. These systems transport CO_2 at -20°C and 20 bar. However, tankers are unlikely to be relevant to large-scale CTSC, and uneconomical compared to pipelines and ships, except on a very small scale (IPCC, 2005).

The transported CO_2 can be either stored or reused in industries.
The principal methods of CO_2 storage are as follows (IPCC, 2005):
- Geological storage: where CO_2 is injected to geological formations, for example depleted oil and gas reservoirs, to enhance oil or gas recovery.
- Ocean storage: in this case, CO_2 is 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 is still in research phase.
- Mineral Carbonation or Mineral Sequestration: is based on the reaction of CO_2 with calcium or magnesium oxide to form insoluble carbonates.

IPCC experts propose another alternative for reducing CO_2 emissions. This alternative is industrial utilization of CO_2. CO_2 is already used in production of chemicals such as urea, refrigeration systems, inert agent for food packaging, beverages, welding systems, fire extinguishers, water treatment processes, horticulture and precipitated calcium carbonate for the paper industry. CO_2 can be also used for the production of chemicals and polymers, such as polyurethanes and polycarbonates. Production of fuels (like methanol) from CO_2 is another choice if only the source of energy is not fossil-based (IPCC, 2005).

In 2009, two hundred thirteen (213) active or planned projects of CTSC were identified, from which 101 projects are in commercial scale and 62 projects are considered as integrated (Global CCS Institute, defines a commercial scale project as the one with a storage rate of 1 Mt/year or more. *An integrated project is where the capture, transport and storage components are undertaken by a single project owner or operator*). Seven of these 62 integrated projects are already in operation (3 projects in the US, 2 projects in Norway, 1 in Canada and 1 in Algeria). These seven projects are collectively storing less than 10 Mt/year. Therefore, to achieve the global CO_2 emissions reduction target by CTSC (10.1 Gt/year by 2050), it is required to increase the annual rate of storage of the existing commercial scale projects by 1000 times (GCCSI, 2009). International Energy Agency (IEA) anticipates 100 CTSC projects globally by 2020, and 3400 projects in 2050. (IEA, 2010)

A brief introduction of CTSC technology was presented in this section. In the following section, we discuss why a novel risk analysis methodology is necessary for CTSC, and why system dynamics approach is appropriate for risk analysis of CTSC chain. Then, we present some examples of systemic risk assessment approaches.

2. CTSC and Risk Assessment

2.1. Necessity of a new risk analysis approach for CTSC

So far, several works have been carried out on risk management of CTSC. However, most of them involve one subsystem and essentially technical aspects of risk. (Fabriol, 2009; Bouc *et al.*, 2009; Savage *et al.*, 2004; PTRC, 2004; Benson, 2002; Perry, 2005; Koornneef *et al.*, 2010; IRGC, 2009) [2]

Lessons learned of industrial disasters show that a combination of technical, organizational and human constituents of risk results in occurrence of accidents (ARIA Inventaire, 2010; Paté-Cornell, 1993; Jasanoff, 1994). Therefore, we recommend to develop an integrated framework of risk analysis for CTSC. The novelty of this framework is the possibility to study the interactions of technical, organizational and human aspects of risk for CTSC system. Moreover, our approach is a dynamic approach that allows studying the risks during the life cycle of the project or any desired time scale. To fulfill this target, we propose to integrate system dynamics and risk analysis methods to develop a dynamic risk analysis framework for CTSC. This approach allows us to consider the interconnections of different variables which could make a failure happen in the system.

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[2] *Some studies are available on CTSC integrated risk analysis. For instance, DNV report on HSE issues related to large-scale capture, transport and storage of CO_2 (Johnsen et al., 2009). In this study, an almost integrated analysis has been carried out, including capture, transport and injection phases (storage phase is not included).*
Another example of integrated risk analysis is the study performed for Belchatow project, in Poland. Technical, financial, organizational, socio-political and regulatory risks associated with a large-scale CTSC project have been studied in this project. (Kerlero de Rosbo, 2009)

2.2. Why system dynamics approach for risk assessment of CTSC?

System dynamics is a methodology to understand the structure and the behavior of complex systems, created during the mid 1950s by Jay W. Forrester in the Massachusetts Institute of Technology (MIT).

From then on, 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, 2004; Stringfellow, 2010; Garbolino *et al.*, 2009; Garbolino *et al.*, 2010).

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 interface between organizational, human and technical aspects could initiate a failure in the system. System dynamics is an appropriate tool to study the interactions of CTSC elements.

The definition of system, complex system, and sociotechnical system may be required to recall here. Durand (1979) presents six definitions for "system", made by different philosophers and scientists. Most of the definitions highlight the notion of "interrelations" between the elements of the system. For instance, "system is a global unit organized by interrelationships between elements, actions or individuals" according to Edgar Morin (French philosopher and sociologist) (Durand, 1979).
A "Complex System" is a system in which the behavior of the whole cannot always be explained in terms of the behavior of the individual parts. In other words, in a complex system, the dynamic interaction of components is more essential than the components themselves. This definition of complex system will be used throughout this paper.
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. (see Figure 1)

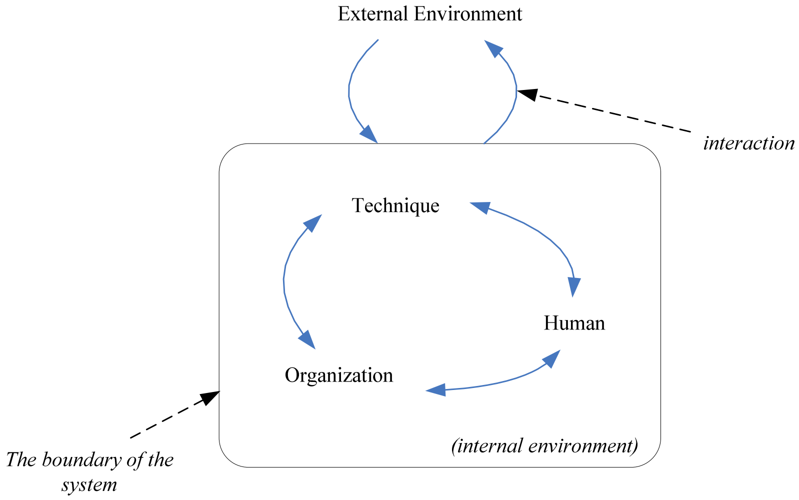

Figure 1: Model of a sociotechnical system

2.3. Recent applications of system dynamics in risk assessment

Safety management approaches has evolved according to the lessons learned from industrial accidents (figure 2). Until 1960, technical aspect was the main focus of attention. Afterwards, human error was brought forward as a significant factor in safety management. By mid 1980, lessons learned from the disasters like Three Mile Island, Bhopal, Chernobyl and Challenger led to the entrance of organizational and management issues into safety management world. Safety culture and resilience are the most recent concepts in this field. (Cambon, 2007)

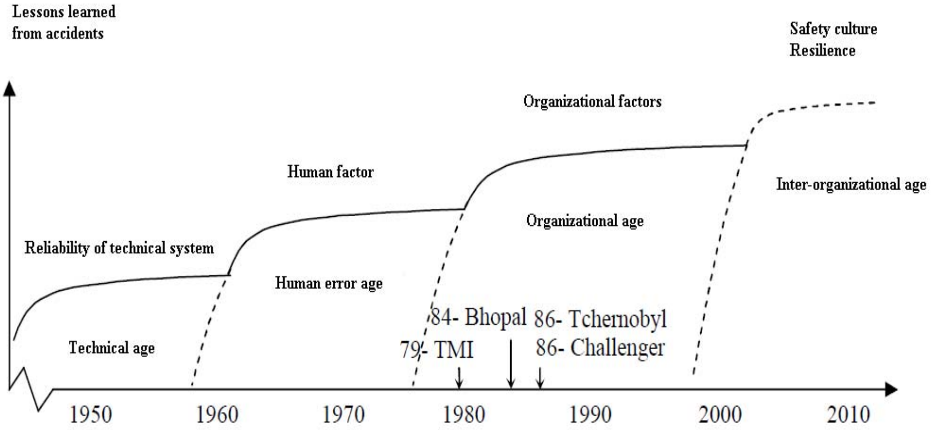

Figure 2: Evolution of safety management approaches
(translated from Cambon, 2007)

Recent methods of safety management and risk assessment are more systemic. These methods place emphasis on the interactions of the system's elements that will give rise to the risks. System dynamics is one of the recent approaches applied for analyzing risks and accidents. In this section we review some examples of such application.

The first example is a systemic accident model, developed by Leveson in the domain of aeronautics. As Dulac (2007) states: "*to manage risk in complex engineering systems, it is necessary to understand how accidents happen*" [3]. "*As the complexity of engineered systems increases, new types of accidents have started to emerge that result from the dysfunctional interactions between system components. These accidents result from unplanned or unexpected interactions between different components of a system, rather than single (or multiple) component failure*" (Dulac, 2007) (Second quotation from (Leveson, 2004)). Accidents are categorized in two groups: event-chain accidents and system accidents. Event-chain accident is an accident which happens as a result of a series of events, whereas system accident results from cascading failures (Perrow, 1999).

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[3] *Accident's definition: an unplanned and undesired loss event which results in human, equipment, financial or information losses. (Leveson, 2009)*

Traditional risk analysis methods, such as Failure Modes and Effect Analysis (FMEA), Fault Tree Analysis (FTA) and Probabilistic Risk Analysis (PRA), are based on event-chain accident approach. Therefore, the traditional methods of risk analysis are not appropriate for complex systems, because the interactions between different components of the system are not considered in these methods (Dulac, 2007).

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 and particularly on Rasmussen's idea that called into question *the usual approach of modeling sociotechnical systems by decomposition of elements* (Rasmussen, 1997). Different actors of the system, from legislatures to company's top management, project management, operations management and lower levels are taken into account in Leveson’s sociotechnical model. She argues that lack of constraints imposed on the system design and on the operations is the main cause of an accident, instead of a series of events. Leveson believes that we need to review the control actions already available in the system in order to understand why accidents happen and prevent losses in future. 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. (Leveson, 2004)
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.

More recently, Garbolino *et al*. (2010) have presented a dynamic risk analysis approach for a Cl_2 storage and transport unit. 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. Garbolino *et al*. have selected the STELLA$^{®}$ software to perform dynamic modeling.
In the 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.

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

3. Proposed methodology

In this section, we explain our proposed methodology for developing an integrated risk analysis framework for CTSC activities. The purpose is to apply system dynamics modeling as a support for risk analysis of CTSC system. Modeling CTSC system allows us to evaluate the reliability of the available safety control system to avoid the catastrophic situations. Consequences of a minor deviation from the normal operation mode in the whole system could be studied by this approach. Furthermore, the effect of a combination of failure scenarios on the entire system could be analyzed.

Our methodology is based on what was described in section 2.3. as "systemic approaches". The outline is illustrated in the following figure:

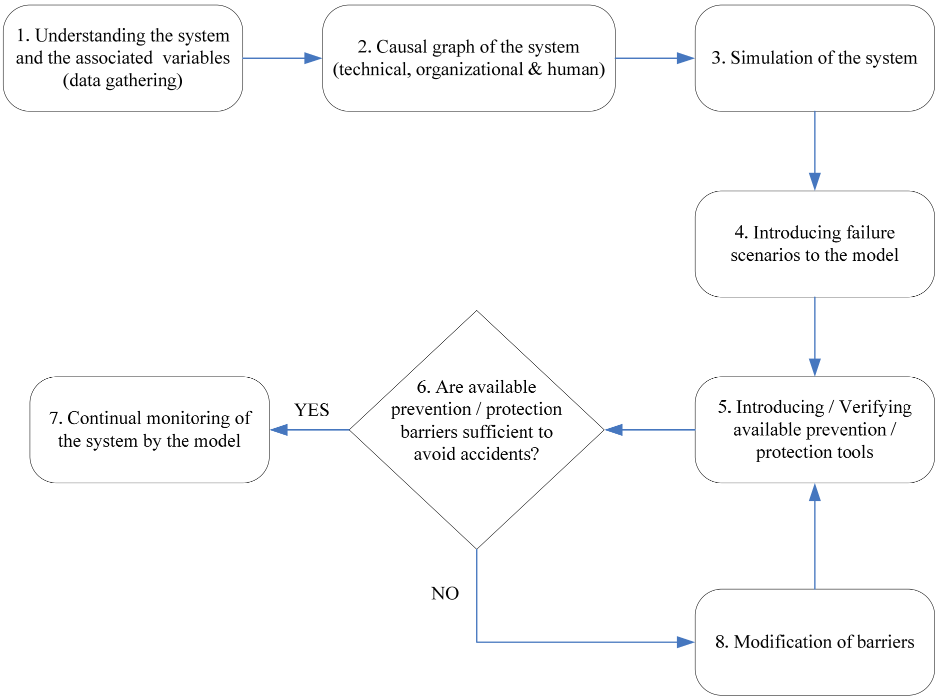

Figure 3: Outline of the methodology

1. In the first step, we gather the required data through literature review, engineering data of CTSC projects (if available) and interview with experts. Engineering information such as process flow diagrams, piping and instrumentation diagrams, process descriptions, cause and effect diagrams and risk analysis reports provide us with a list of technical variables to be modeled subsequently. Process conditions (pressure, temperature, flow rate, concentration, etc.) and control instruments (control valves, pressure safety valves, pressure and temperature switches, etc.) are the most significant elements that should be considered in the model. For the human and organizational part, we use the organization charts and project’s information to form a hierarchical structure of the system and the role of each person concerning safety control. Experience, education, training, motivation, stress, working conditions and communication are some of the major human and organizational variables pointed out in several literature (Stringfellow, 2010; Simba Ngabi, 2006; Kerlero de Rosbo, 2009; Hollnagel, 1998).

Listing the main variables is the prerequisite of the next step, where we develop the causal graphs of CTSC system.

2. The interactions of the most significant elements of the system are illustrated in causal graphs.
   Our main purpose is to assure that the safety control system in CTSC whole chain is reliable. The overall causal graph of the system is illustrated in the following figure. The performance of each technical sub-system affects the performance of others. The organizational and human performances have an impact on the performance of safety management system, which is in direct interaction with the performance of our technical system.

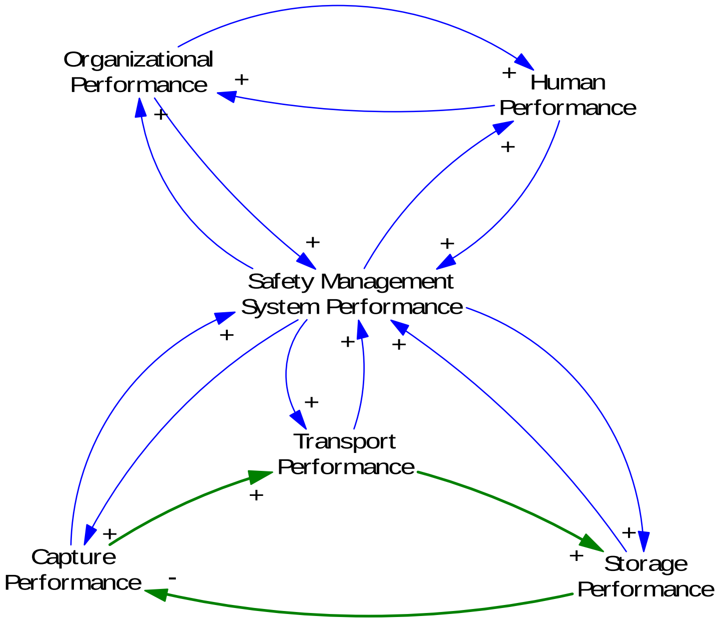

Figure 4: Overall causal graph

3. After structuring the static model, we can simulate the system to follow up the evolution of the system over time.
4. So far, the system has been modeled in normal operation mode. The subsequent step is to introduce failure scenarios to the model to see what happens in case of each failure. Failure mode model allows us to compare the behavior of the system in normal operation and failure modes.
5. Afterwards, the available prevention or protection tools (such as alarms, controls, procedures) are introduced in the model.
6. In this stage, we should answer this question: "Are available prevention/protection tools sufficient to avoid accidents?"
7. The positive answer to the question means that the available safety control system is reliable. However, the behavior of the system should be continually monitored by the model.

8. If the answer is negative, the barriers should be modified and reintroduced to the model.

The main phases of the methodology were presented in the preceding paragraphs. Now, we will analyze our case study and the methodology's application for the case study.

Our case study is an integrated CTSC system as illustrated in figure 5. The main steps of the integrated process are indicated in figure 5. CO_2 capture process is an oxycombustion process. In this process, CO_2 is captured from a natural gas stream. The only chemical reaction occurs in the boiler between the natural gas and gaseous oxygen, coming from the Air Separation Unit (ASU). The boiler outlet is washed and cooled down in the gas treatment section. CO_2 stream is then compressed in a three-stage compressor. An inter-cooler cools down the outlet of each stage in order to separate the water from the main CO_2 stream. The outlet pressure of compressor is about 27 bara. The last stage of the capture process is drying the CO_2 stream in a molecular sieve unit. Afterwards, CO_2 is transported to the storage location through a pipeline of about 30 kilometers.
CO_2 is compressed again before being injected into a depleted gas reservoir at a depth of 4500 meters.

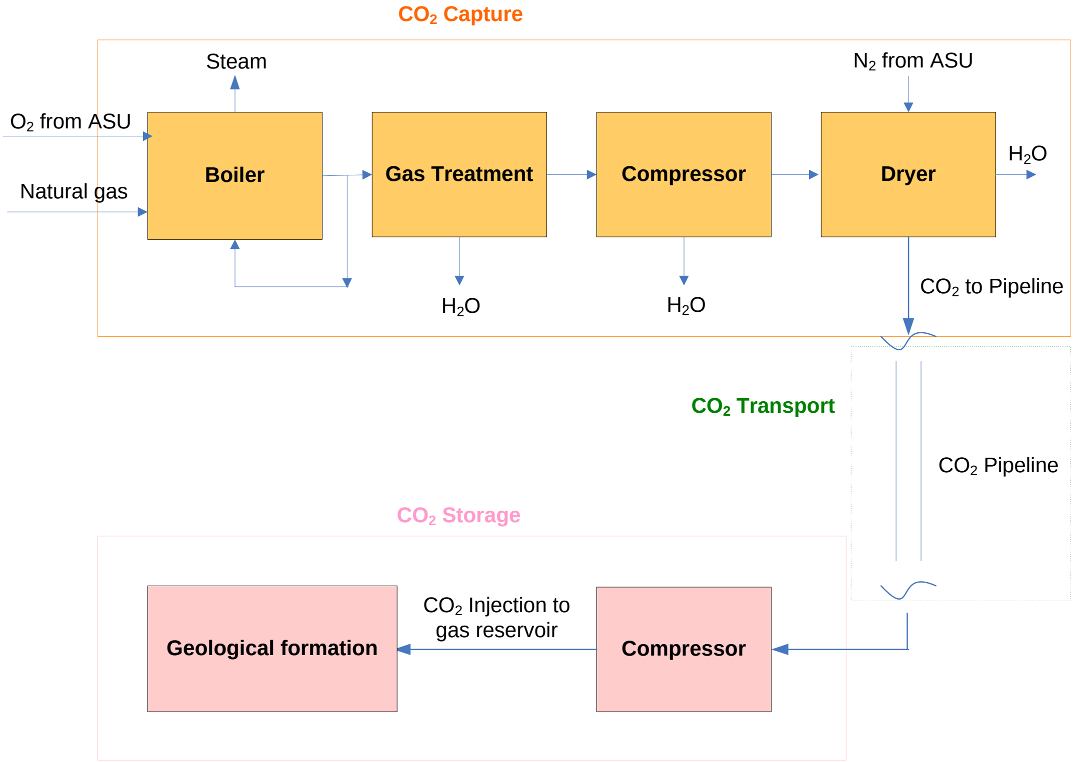

Figure 5: Case study, integrated CTSC system

As explained previously, the first action is to list the most significant variables that should be controlled in the system illustrated in figure 5. Subsequently, the causal graphs are developed for the case study. Principal technical variables of the case study are presented in figure 6. In this figure, the main variables of capture, transport and storage are separated out. The positive (+) and negative (-) marks in figure 6 indicate the positive and negative relationships. We have started developing the causal graph from the five major variables that should be controlled during the life cycle of the project (indicated in bold in figure 6). These variables are explained in the following paragraphs.

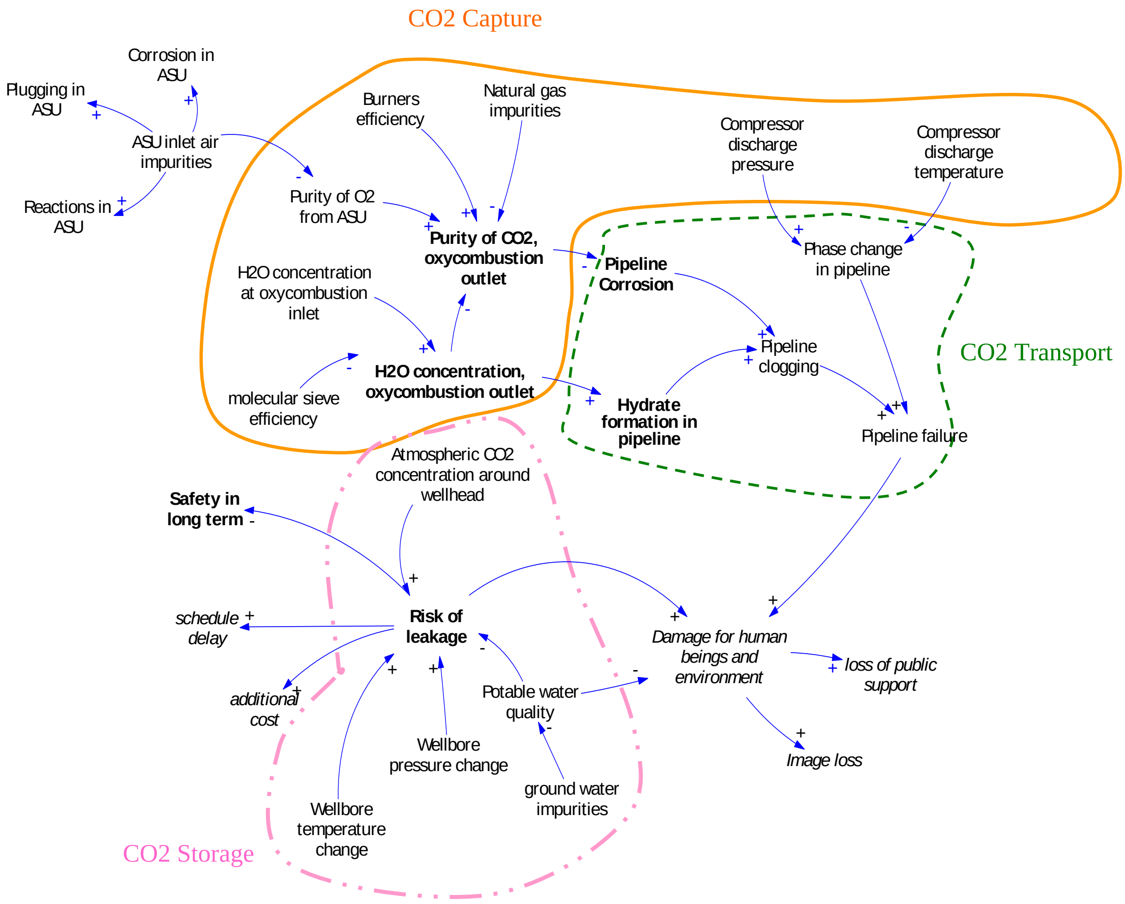

Figure 6: CTSC causal graph, technical variables

Two major variables of CO_2 capture process are as following:

1. “Purity of CO_2, oxycombustion outlet”:
   The purity of CO_2 in the outlet of dryer is a crucial variable, because it could result in corrosion and clogging in the pipeline. Hydrocarbons, H_2S and water are the most significant impurities that could cause corrosion.
   CO_2 purity in the outlet of dryer depends on the purity of boiler feeds, i.e. oxygen and natural gas, and the efficiency of burners.
   As represented in figure 6, the purity of oxygen from ASU is influenced by the purity of inlet air to the Air Separation Unit.

“ASU inlet air impurities” could also result in corrosion, plugging or undesired reactions in the Air Separation Unit. ASU is not considered in the boundary of CO_2 capture unit (figure 5). Therefore, the parameters concerning ASU are not shown in the same group as the variables of CO_2 capture.

2. “H2O concentration, oxycombustion outlet”:
   The concentration of water in the outlet of CO_2 capture unit is the second major variable of CO_2 capture system. The variation of water concentration will affect the purity of CO_2 (figure 6). The water is absorbed in several sections of CO_2 capture unit, including the treatment unit, the compressor and the dryer (as illustrated in figure 5). Therefore, separating water from the main CO_2 stream is crucial. The presence of water in the pipelines results in hydrate formation, corrosion and pipeline clogging.
   As represented in figure 6, “H2O concentration at oxycombustion inlet” (the amount of water in natural gas), and “molecular sieve efficiency” (i.e. dryer’s efficiency) affect the quantity of outlet water.

The other two main variables are related to CO_2 transport system:

3. “Pipeline corrosion”:
   “Sweet gas corrosion” or “carbonic acid corrosion” is a major source of damage in pipelines (Barrie *et al.*, 2004). Carbonic acid corrosion refers to the corrosion in pipelines when CO_2 reacts with water and form carbonic acid. As explained previously, the presence of water in CO_2 pipeline could be interpreted as CO_2 stream impurity. This impurity will result in pipeline corrosion, and clogging as well.

4. “Hydrate formation in pipeline”:
   Hydrate formation in pipeline is the second principal variable to be controlled in CO_2 transport system. Hydrate is a kind of solid ice-like crystal which is formed in case of the presence of water in pipeline. CO_2 enters the water lattice and forms the hydrate. Hydrate formation could reduce the pipeline flow capacity and plug the transport system (Serpa *et al.*, 2011). For this reason, the concentration of water in CO_2 pipeline in a critical point.

The compressor discharge pressure or temperature change create two-phase stream in the pipeline. “Phase change in pipeline” increases the chance of pipeline failure (Serpa *et al.*, 2011).

The last major variable is “risk of leakage” that concerns to the storage system.

5. “Risk of leakage”:
   Our principal goal is to maintain the reliability of the safety control system in long term. The leakage of CO_2 is a parameter that directly affects the safety in long term. Wellbore pressure change, wellbore temperature change, atmospheric CO_2 concentration around wellhead, and the quality of potable water are the variables that could indicate CO_2 leakage from the reservoir.

As shown in figure 6, CO_2 leakage or pipeline failure could give rise to damage for human beings and environment, and accordingly loss of public support and the project's owner image loss. Delay in project's schedule and additional cost are the other ultimate consequences of CO_2 leakage. To maintain the safety in long term, the risk of CO_2 leakage should be reduced. These latter parameters are represented in italic in figure 6.

The organizational and human causal graph is illustrated in figure 7. The objective of this paper is not to detail all the organizational and human variables and their interconnections. Nevertheless, we make a summary in this section.
We have started from the major variable (safety in long term). The causal graph has been developed based on the items that could affect the main variable. The variables of figure 7 are selected according to some literature on the organizational and human aspects of risk (Jones, 2005; Rudolph and Repenning, 2002; Groeneweg, 2002; Bouloiz, 2010; Stringfellow, 2010; Simba Ngabi, 2006; Kerlero de Rosbo, 2009; Hollnagel, 1998).

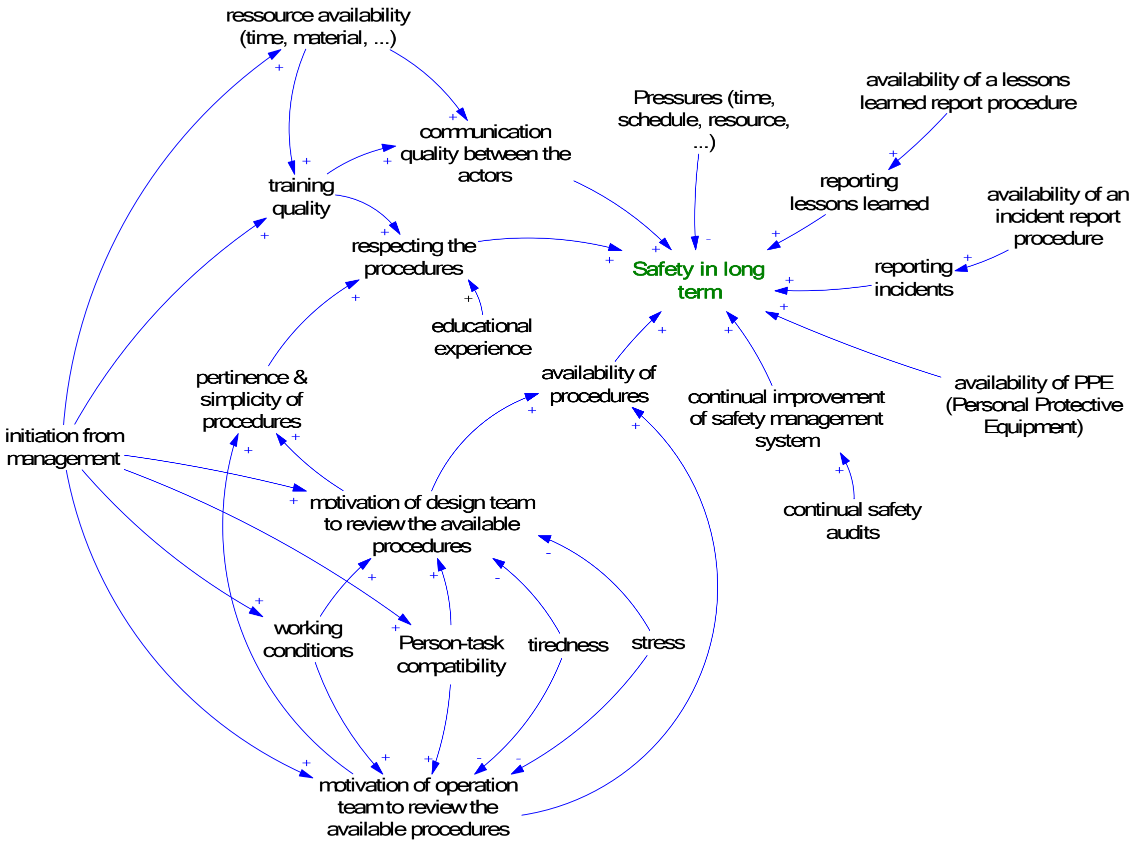

Figure 7: CTSC causal graph, organizational and human variables

As illustrated in figure 7, the following parameters have a direct influence on the "safety in long term": pressures (such as time, schedule and resources), quality of communication between the actors of the system, availability of procedures, respecting the procedures, continual improvement of safety management system, availability of Personal Protective Equipment, reporting the incidents and lessons learned during the life cycle of the project. However, all the other variables of figure 7, which have an indirect feedback on the “safety in long term”, have the same significance in achieving the final goal.

Obviously, we need to quantify the variables in order to simulate the behavior of the system over time. Nevertheless, quantifying the human and organizational variables ("*soft variables*") is a challenge that needs more research. We should recall Coyle's question here: "*How much value does quantified modeling add to qualitative analysis*?" (Coyle, 2000)

The application of the methodology for a case study was presented in the preceding paragraphs. Another potential case study for testing our methodology is a CTSC pooling network, which is in phase of feasibility study. This case is more complicated, because several CO_2 emitter industries (power plants, oil refineries, chemical and petrochemical plants, cement production units, etc.) are involved in pooling network. Since the engineering work of this case has not been carried out, the required information are not completely available. Therefore, the methodology will be adapted for the second case.

4. Conclusion and future work

In this paper, we proposed a new framework of risk analysis for Capture, Transport and Storage of CO_2 (CTSC). The framework has two novel aspects: integrated and dynamic. System dynamics has been applied to understand the structure of CTSC system. Subsequently, the integrated risk analysis framework has been developed by applying system dynamics as a support of risk analysis for CTSC complex system. The ultimate goal is to maintain the safety control system reliable. The technical, human and organizational elements playing a role in realizing this goal have been modeled. For the moment, we have developed a static model for a CTSC case study. Two separate models are developed for the technical and organizational/human systems. The next step is to merge these two models. In this step, feedbacks appear due to human-machine interfaces. The simulation and models of failure scenarios are under development. Nevertheless, a question is still open to answer. The question is: to what extent quantifying the soft variables will be helpful for the risk analysis? Further research is required to answer this question.

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