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Dynamic Analysis of Safety Performance Indicators for CO₂ Capture, Transport and Storage Activities

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Capture, Transport and storage of CO₂ (CTSC) is a novel technology for mitigating CO₂ emissions in the atmosphere and reduce the climate change impacts on ecosystems, human beings and natural resources. However, potential technical, environmental, health, safety and social risks associated with CTSC activities should be studied in order to reassure the stakeholders that CTSC will not have adverse effects on human beings and environment. CTSC can be considered as a complex socio-technical system, for which traditional risk management approaches are not appropriate. An integrated approach is required for risk management of CTSC. The integrated approach should cover the interactions of capture, transport and storage, as well as the technical, organizational and human aspects of risk. The purpose is to evaluate the performance of safety control system in CO₂ Capture, Transport and Storage chain. The idea is to develop a dynamic risk management framework by modeling the principal variables that are significant in terms of safety of CTSC, and study the evolution of these variables over time. These variables can be the ones that are integrated into the Safety Management System (SMS) in order to implement them into a scorecard containing the variation of key performance indicators over time, both in normal operation of the system, and in case of a failure. In this context, system dynamics is used for modeling. The model will allow us to know how the interaction of different variables (technique, organizational or human) may result in variation of performance indicators. The proposed methodology is based on eight steps that will be presented in the paper. The proposed framework is applied to an integrated CTSC project with an enterprise as the owner, and several firms and organizations as operators, designers and stakeholders. In this paper, the approach will be explained in detail and some preliminary results will be presented.

1. Performance indicators and risk management in CTSC activities

1.1 CTSC and risks

CTSC refers to the chain of processes used to collect or capture a CO₂ gas stream, transport the CO₂ to a storage location and inject it into that location. The most significant source of CO₂ emissions is the combustion of fossil fuels such as coal, oil and gas in power plants, automobiles and industrial facilities. Carbon dioxide is a harmless, non-flammable gas (at normal temperature and pressure, i.e. 20 °C and 1 atm.), a constituent of the atmosphere and a necessary ingredient in the life cycle of animals, plants and human beings. According to the standards, a concentration of 0.5 % is acceptable for a continuous exposure to CO₂, while it will be dangerous if the concentration is more than 5 % (IPCC, 2005). The risks concerning Capture, Transport and Storage of CO₂ could be summarized as following:

- Risks associated with CO₂ Capture: The most fundamental risks in CO₂ capture processes are associated with the vent gas produced from the capture plant, as well as liquid and solid wastes.

The captured CO₂ stream may contain impurities which would have practical impacts on CO₂ transport and storage systems and also potential health, safety and environmental impacts. Moreover, CO₂ from most capture processes contains moisture, which has to be removed to avoid corrosion and hydrate formation during transportation. (IPCC, 2005)

- Risks associated with CO₂ Transport: These obviously depend on the transportation mode and on the local topography, meteorological conditions, population density and other local conditions. But in general, carbon dioxide leaking from pipelines or other modes of transportation could result in potential hazards for human beings and animals. (IPCC, 2005)
- Risks associated with CO₂ Storage: According to Svensson (BRGM, 2005), there are two types of risks concerning geological storage of CO₂, "local risks" and "global risks". As the examples of local risks, he points out the risks for human beings, animals and plants above ground, contamination of potable water, interference with deep subsurface ecosystems, ground heave, induced seismicity, damage to mineral or hydrocarbon resources. The most significant example of global risks is the release of CO₂ in the atmosphere.

1.2 Performance indicators: a brief introduction

The purpose is to evaluate the performance of safety control system in CO₂ Capture, Transport and Storage chain. The idea is to develop a dynamic risk management framework by modeling the principal variables that are significant in terms of safety of CTSC, and study the evolution of these variables over time. The output is a scorecard containing the variation of key performance indicators over time, both in normal operation of the system, and in case of a failure. System dynamics is used for modeling. The model will allow us to know how the interaction of different variables (technique, organizational or human) may result in variation of performance indicators.

"Performance" is defined as following in dictionaries:

- "the ability to perform; the manner in which a mechanism performs" (Meriam Webster)
- "how well a person, machine, etc. does a piece of work or an activity" (Cambridge)
- "how well or badly you do something; how well or badly something works" (Oxford advanced)

In the field of management, performance means "all the elements that contribute to meet the strategic objectives" (Lorino, 2003, p. 9). Performance could be measured by performance indicators. According to Fernandez (2010), "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 "an information that should help an actor, an individual or a group to carry out the activities in order to meet the objectives; or help them to evaluate the results" (Lorino, 2003, p. 130). Performance indicators could be categorized in two principal groups: (Step change in safety, 2009)

- Lagging indicator: "*measure the outcomes that have resulted from past actions*", for example the log of a boat that provides information on the boat speed and the distance covered. Lagging indicators monitor output or results.
- Leading indicator: "*measure the inputs to the process that will affect future outcomes*", for example the compass, wind indicator and radar in the boat. Leading indicators monitor input.

In the next section, we present the methodology proposed to assess the performance of CTSC safety control system.

2. Methodology of performance assessment and the role of system dynamics

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). He defines system dynamics as a combination of the theory, methods and philosophy needed to analyze the behavior of systems (Forrester, 1991). So far, 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. In order to evaluate the performance of safety control system in CO₂ Capture, Transport and Storage chain, the principal variables in terms of safety of CTSC are modeled by a system dynamics software (VENSIM®). The behavior of variables over time is studied to provide a scorecard containing the variation of key performance indicators.

1. In the first step, we define the problem according to the literature review and discussions with experts. Documents of project could also be helpful to correctly describe the problem. The main purpose is to assure that the safety control system in CTSC whole chain is reliable. Therefore, the problem is rephrased as the "Evaluation of the performance of the safety management system of CO₂ Capture, Transport and Storage chain".
2. The second stage is to develop the overall causal graph. The interactions of the most significant elements concerning the identified problem are illustrated in the overall causal graph. CO₂ Capture, Transport and Storage is a complex socio-technical system, where the technical sub-system is in interconnection with the organizational and human sub-systems. The overall causal graph of the system is developed according to this idea.
3. After structuring the overall causal graph, and in order to start the dynamic modeling (4th step), we need to develop some detailed causal graphs. Detailed causal graphs contain the interactions of the most significant variables that represent the variables of the overall causal graph.
4. The fourth step is to model the variables, developed in the previous stages, by system dynamics software. In this part, we use VENSIM® to model the normal operation of the system. Normal operation is the phase when everything is going well, as we have expected or designed. The output of this stage is a scorecard of normal operation mode, with the variation of key performance factors over time.
5. In this step, we model the failure scenarios, to study how the deviation of some variables could affect the key performance indicators. The failure scenarios could be selected based on the results of risk analysis, the deviation cases pointed out in the literature, or even according to the documents of the case study or expert's opinion.
6. After simulating the deviations, and having the behavior of KPIs in case of a deviation, we compare the KPI behavior over time with the desired KPIs. The reference for desired KPIs could be the literature, the experts' points of view, project documents, or even the output of the fourth step, i.e. the behavior of KPIs in normal operation.
7. If there is a difference between the calculated and desired KPIs, recommendations should be provided to add or modify the control barriers.
8. In case of no difference between the calculated and desired KPIs, we should continue to monitor the KPIs by the model.

A case study will be presented in the next section, and the application of the methodology for the case study will be discussed.

3. Case study and preliminary results

The case study is an integrated CTSC project. The purpose is to inject the flue gas produced in a natural gas production unit to a depleted gas reservoir. The gas will be injected during two years, and then the storage site will be monitored during three years, before transferring the responsibility to the government. CO₂ capture process is an oxycombustion process. In this process, CO₂ 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. CO₂ 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 CO₂ stream.

Table 1: Capture and Transport Key Performance Indicators

	Factors concerning capture and transport performance	Lagging KPI	Desired KPI
1	Percentage of captured CO ₂	Injected CO ₂ flow rate / Captured CO ₂ flow rate	0.9
2	Purity of captured CO ₂	[CO ₂] (vol% at capture outlet)	87-96

The last stage of the capture process is drying the CO₂ stream in a molecular sieve unit. Afterwards, CO₂ is transported to the storage location through a pipeline. CO₂ is compressed again before being injected into the depleted gas reservoir at a depth of 4500 m (Samadi and Garbolino, 2011). After some discussions with the experts, we summarized the factors describing the performance of capture,

transport and storage of CO₂ and the (lagging) key performance indicators (lagging KPI) in the following tables:

Table 2: Storage Key Performance Indicators (adapted from Desroches, 2011)

Factors concerning storage performance	Lagging KPI
1 Capacity	Available pore volume & Efficiency of trapping
2 Containment	Sealing of barriers & Leakage rate
3 Injectivity	Injected CO ₂ flow rate

An example of the overall view of CTSC system translated into a system dynamics modeling is illustrated in Figure 1. The main idea is to model one of the key performance indicators of capture and transport (Injected CO₂ flow rate / Captured CO₂ flow rate, previously presented in Table 1). The variables presented in boxes (such as “Captured CO₂”) are the stock variables (accumulations in the system). The variables presented in arrows, accompanied a valve (such as “O₂ from ASU”), are the flow variables (flows between the stocks). The other variables of Figure 1 are the auxiliary or control variables (computed from other variables). The time scale considering for the simulation is 2 years, the duration of the injection phase.

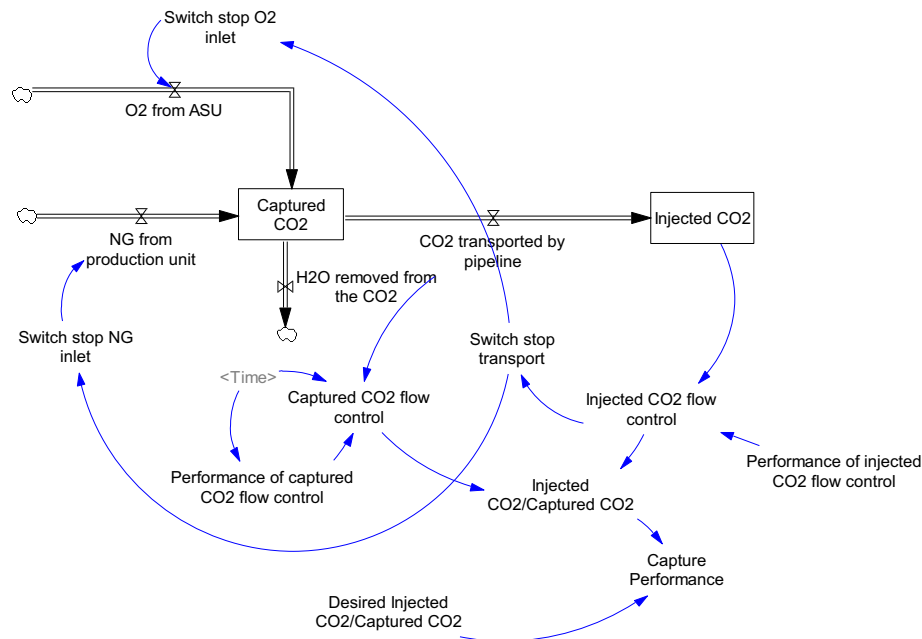


Figure 1: Overall CTSC chain, translated in system dynamics model

In this example, “O₂ from ASU” and “NG from ASU” are the inlets of the stock “Captured CO₂” (O₂: Oxygen, NG: Natural gas). We defined “Captured CO₂” as a stock representing CO₂ capture process, which should be zero due to the fact that the following equation is considered:

$$O_2 \text{ from ASU} + \text{NG from production unit} = \text{CO}_2 \text{ transported by pipeline} + \text{H}_2\text{O removed from the CO}_2$$

The measurement unit for all the above mentioned variables is ton/year. For the moment, the input flow rates to the capture process (i.e. Oxygen and Natural Gas) are not considered variable over time. Whereas, the flow rate of oxygen and natural gas is inevitably variable in reality (This could be added in the simulation). A flow rate of 9.5 t/h and 2.3 t/h is respectively considered for oxygen and natural gas. (The assumption is that the process is in service 360 days per year and 24 hours per day, which is not a realistic. This assumption should be changed in next steps. “CO₂ transported by pipeline” is set to

60,000 t/y, since the purpose of the project is to inject 120,000 ton CO₂ in the reservoir in two years. Two simulation cases are defined: "Normal Operation" and "Performance of captured CO₂ flow control". In Normal Operation, "Performance of injected CO₂ flow control" and "Performance of captured CO₂ flow control" are equal to 1, and do not change over time. "Performance of captured CO₂ flow control" simulation case is the case where "Performance of captured CO₂ flow control" is variable over time. The variability of this performance is a function of various parameters, including the organizational and human key performance indicators. The assumed variability of "Performance of captured CO₂ flow control" is as follows:

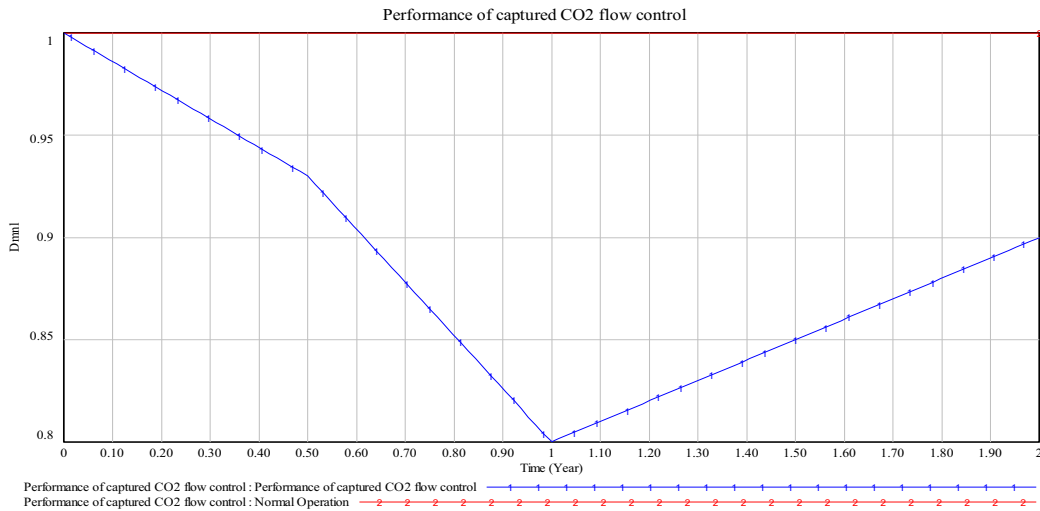


Figure 2: Variation of "Performance of captured CO₂ flow control"

As a result, "Injected CO₂/Captured CO₂" (which is a key performance indicator) will be as follows:

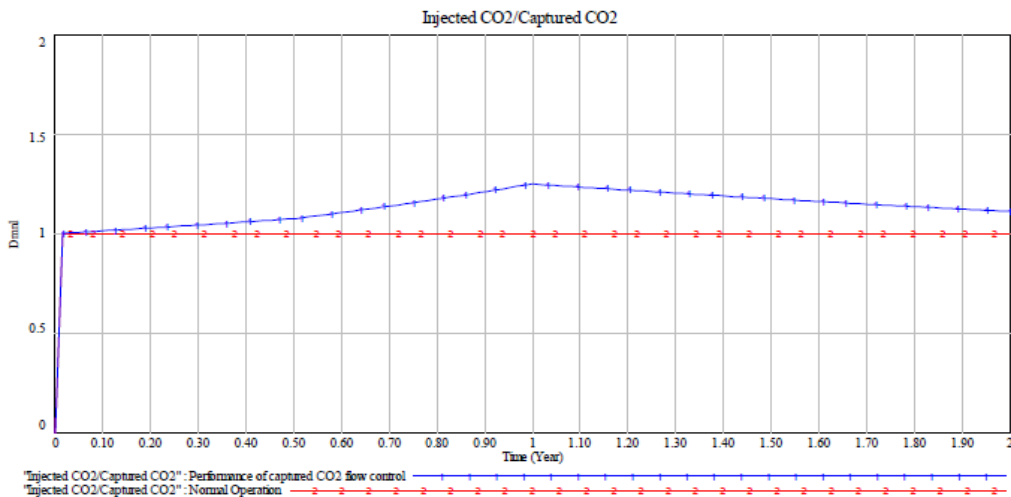


Figure 3: Variation of "Injected CO₂/Captured CO₂"

With all the assumptions made for this example, we can see that the variation of our indicator, "Injected CO₂/Captured CO₂", remains in the acceptable range, i.e. greater or equal to 0.9 (Desired Injected CO₂/Captured CO₂).

4. Conclusion and perspectives

Most of the existing works on risk management of CTSC do not study the whole chain of capture, transport and storage. They are also basically focused on the technical risks associated to CTSC, although lessons learned from industrial disasters place emphasis on the significance of organizational and human aspects of risk. In most of the cases, a set of technical, organizational and human problems leads to an incident or an accident. Based on this fact, the purpose of our research project is to develop an integrated dynamic risk management framework, by modeling the main variables regarding safety in a CTSC integrated chain. The variation of key performance indicators over time is studied by system dynamics modeling. System dynamics modeling allows us to understand and study the interconnections of the system's elements, the behavior of variables over time, the impact of variations with different amplitudes on the behavior of CTSC whole chain. We can also anticipate the deviations from designed or desired conditions. An example of simulation with VENSIM® was presented. In this example, the purpose was to study the variation of a key performance indicator of the chain, which is the ratio of injected CO₂ to captured CO₂. Two simulation cases have been considered: "Normal Operation" and "Performance of captured CO₂ flow control". In "Normal Operation" case, the variable "Performance of captured CO₂ flow control" is equal to 1, and does not change over time. In "Performance of captured CO₂ flow control" simulation case, "Performance of captured CO₂ flow control" is variable over time. "Injected CO₂/Captured CO₂" has been calculated in two simulation cases. A control parameter (Desired Injected CO₂/Captured CO₂) is considered for comparing the value of the ratio "Injected CO₂/Captured CO₂" with a desired value (desired KPI). With the assumptions that we made for the simulation, the ratio remains in an acceptable range. However, we should take decisions by taking into consideration not only the lagging indicators, but also the leading ones. In the presented example, the lagging indicator (Injected CO₂/Captured CO₂) seems to be acceptable. Nevertheless, the leading indicators such as "Performance of captured CO₂ flow control" should be also analyzed to make sure about the performance of control system. In the present article we focused on safety, which is one of the aspects of risk associated with CTSC. However, an integrated risk management approach should also cover other aspects such as political, social, legal and financial ones.

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