Interdependent Ranking of Sources and Sinks in CCS Systems using Analytical Network Process

M. A. B. Promentilla\textsuperscript{a}, J. F. D. Tapia\textsuperscript{a,b}, C. A. Arcilla\textsuperscript{c}, N. P. Dugos\textsuperscript{a}, P. D. Gaspillo\textsuperscript{a}, S. A. Roces\textsuperscript{a} and R. R. Tan\textsuperscript{a,b}\textsuperscript{*}

\textsuperscript{a} Chemical Engineering Department  
\textsuperscript{b} Center for Engineering and Sustainable Development Research  
De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines

\textsuperscript{c} National Institute of Geological Sciences, University of the Philippines-Diliman, C.P. Garcia corner Velasquez Street, 1101 Quezon City, Philippines

\textsuperscript{*} Corresponding Author’s E-mail: raymond.tan@dlsu.edu.ph

Abstract

$CO_2$ capture and storage (CCS) is widely regarded as a key technology for reducing greenhouse gas emissions from large industrial point sources. It entails the capture of a relatively pure $CO_2$ from exhaust gases using different techniques, and then storing this captured gas in various geological sinks. Large-scale deployment of CCS requires the comprehensive evaluation of candidate sources and sinks present in a given geographical region. In this study, we propose an analytic network process (ANP) approach to rank simultaneously the potential $CO_2$ sources and sinks in a CCS system. This ANP decision model allows us to incorporate the feedback dependency that exist in the preference ranking of sources and sinks due to the importance of geographic proximity as a decision criterion. A case study is then solved to demonstrate the proposed model.

Keywords: $CO_2$ Capture and Storage; Decision Analysis; Analytic Network Process

1. Introduction

Carbon capture and storage (CCS) is an important technology for reducing greenhouse gas emissions from large industrial $CO_2$ sources such as power plants, oil refineries, cement kilns, etc. In CCS, a relatively pure $CO_2$ stream is captured from exhaust gases using various physical or chemical techniques, such as oxy-fuel combustion and pre- or post-combustion capture. This stream is then transported for storage in various sinks, such as saline aquifers, inaccessible coal deposits, and depleted oil and gas wells (Davison et al., 2001). Large-scale deployment of CCS requires the comprehensive evaluation of candidate sources and sinks present in a given geographical region. One of the fundamental problems is to rank these decision elements based on relevant technical criteria (Asian Development Bank, 2012). For example, the sources may be ranked based on annual $CO_2$ flowrate, total capturable $CO_2$ over the entire operating life, age of the facility, intermittency of operation and location. Likewise, the sinks to be evaluated may be ranked based on geological properties that reflect long-term $CO_2$ storage capacity, injection rate limits, structural integrity and geographic location.
Note that the sets of sources and sinks may be ranked using appropriate multiple attribute decision-making (MADM) tools, such as the analytic hierarchy process (AHP) (Saaty, 1980), or the more generalized approach, known as the analytic network process (ANP) (Saaty and Takizawa, 1986). ANP uses the so-called supermatrix representation of a network structure to serve as a general composition principle of ratio-scale priority weights wherein hierarchical composition is a special case (Saaty, 2001). Recent work has demonstrated the usefulness of such techniques in CCS planning. AHP has been applied by Yu et al. (2011) for screening storage sites in Taiwan. More recently, Tan and Promentilla (2012) proposed a modified form of AHP for ranking storage sites upon the introduction of new information. ANP has recently been proposed for the ranking of storage sites based on detailed geological criteria (Hsu et al., 2012). However, none of the existing work have recognized the issue of joint preference ranks of source and sinks in CCS systems.

This paper is organized as follows. Section 2 gives the formal problem statement. The ANP approach is then described in Section 3. A hypothetical but realistic case study is solved in Section 4 to illustrate the methodology. Finally, the last section gives the conclusions and prospects for future work.

2. Problem Statement

In this paper, the formal problem statement is as follows:

- The CCS system consists of $m$ sources and $n$ sinks.
- Each source $i$ ($i = 1, 2… m$) is to be evaluated on the basis of $p$ criteria, where one of the criteria is geographic proximity to available sinks.
- Each sink $j$ ($j = 1, 2… n$) is to be evaluated on the basis of $q$ criteria, where one of the criteria is geographic proximity to available sources.
- The decision problem is to establish the preference ranks for the set of $m$ sources, and likewise to do the same for the set of $n$ sinks. Note that the inclusion of geographic proximity as a criterion for both sources and sinks results in interdependence in the preference ranks.

3. Decision Model for Joint Ranking

The main problem in attempting to rank sources and sinks is the interdependency between the two subproblems. The viability of any given source depends on its proximity to sink options; likewise, the viability of any given sink depends on having nearby sources. As a result, the subproblems of ranking sources and ranking sinks cannot be solved independently of each other, as, clearly, the priority or preference ranking of one set of alternatives influences ranking of the other. A comprehensive decision analytic framework for this problem must take into account the mutual influences of the source and sink ranks. In this work, we propose an ANP approach to handling this problem.

This approach makes use of a hierarchical network decision structure containing the feedback dependence between the source and sink cluster as shown in the digraph. Note that the initial supermatrix representation of the digraph is a partitioned matrix where each submatrix represents the relationship between and within the levels or clusters (Saaty, 2001; Promentilla et al., 2006; 2008). The submatrices $W_{SoSk}$ and $W_{SkSo}$ are composed of set of priority weights to describe the feedback dependence due to
Interdependent ranking of sources and sinks in CCS

geographic proximity between the sources and sinks. On the other hand, the submatrices $W_{SoG_1}$ and $W_{SkG_2}$ are composed of priority weights that measure the relative preference of sources and sinks, respectively, without first considering the geographic proximity. These set of weight can be obtained from an independent hierarchic decision structure wherein the proximity between the source and sink is not considered as one of the evaluation criteria. In addition, the inner dependence loop within each cluster as described by the identity matrix $I$ suggests mutual independence among the elements within the cluster whereas the row vector $e^T$ describes the feedback control loop resulting to a strongly connected digraph. Null matrices $\Theta$ in the initial supermatrix suggest no direct relationship between clusters in the digraph as shown in Figure 1.

\[
\begin{array}{cccc}
G_1 & So & Sk & G_2 \\
G_1 & I & e^T & \Theta \\
So & W_{SoG_1} & I & W_{SoSk} \\
Sk & \Theta & W_{SkSo} & I \\
G_2 & \Theta & \Theta & e^T & I \\
\end{array}
\]

Figure 1. Digraph and its initial supermatrix representing the problem structure

The initial supermatrix representation of this strongly connected digraph when transformed into column stochastic converges to a limit matrix of identical columns as the stochastic matrix is raised to large power. Such column vector in this limit matrix is equivalent to the principal column eigenvector of this supermatrix that provides meaningful ratio-scale priority vectors of dominance of the elements in the cluster as all direct and indirect interactions are captured in the process of convergence. Due to space limitations, the reader is referred to Promentilla et al. (2006; 2008) for details of the computational procedure.

4. Case Study

This example uses source/sink data that is hypothetical, but highly representative of typical CCS planning scenarios (Asian Development Bank, 2012). Relative preferences of CO$_2$ sources and sinks from an independent hierarchical structure which excludes the geographic proximity as a criterion are summarized in Tables 1 and 2. We then use the ANP model described in Figure 1 to account for the interdependence of ranking of sources and sink due to geographic proximity. The procedure for determining these normalized scores from raw physical data is a well-established step in AHP and ANP literature (Saaty, 1980; 2001), and need not be described here in detail due to space constraints. This work focuses on the effect of joint ranking only.
Table 1: Normalized scores from independent ranking of CO₂ sources without considering sink proximity criterion

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂ flowrate (0.30)</th>
<th>Operating Life (0.25)</th>
<th>Capacity Factor (0.25)</th>
<th>Flue Gas Quality (0.20)</th>
<th>Composite scores and ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.217</td>
<td>0.238</td>
<td>0.254</td>
<td>0.3</td>
<td>0.248 (2)</td>
</tr>
<tr>
<td>2</td>
<td>0.435</td>
<td>0.190</td>
<td>0.243</td>
<td>0.3</td>
<td>0.299 (1)</td>
</tr>
<tr>
<td>3</td>
<td>0.130</td>
<td>0.286</td>
<td>0.254</td>
<td>0.3</td>
<td>0.234 (3)</td>
</tr>
<tr>
<td>4</td>
<td>0.217</td>
<td>0.286</td>
<td>0.249</td>
<td>0.1</td>
<td>0.219 (4)</td>
</tr>
</tbody>
</table>

Table 2: Normalized scores from independent ranking of CO₂ sinks without considering source proximity criterion

<table>
<thead>
<tr>
<th>Sink</th>
<th>Storage capacity (0.30)</th>
<th>Injectivity (0.20)</th>
<th>Structural Integrity (0.50)</th>
<th>Composite scores and ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.333</td>
<td>0.364</td>
<td>0.3</td>
<td>0.323 (2)</td>
</tr>
<tr>
<td>2</td>
<td>0.167</td>
<td>0.364</td>
<td>0.6</td>
<td>0.423 (1)</td>
</tr>
<tr>
<td>3</td>
<td>0.500</td>
<td>0.273</td>
<td>0.1</td>
<td>0.255 (3)</td>
</tr>
</tbody>
</table>

Tables 3 and 4 summarize the relative score and preference order of CO₂ sources and sinks before and after consideration of the geographic proximity. The second column of Table 3 shows the normalized overall scores (and resultant ranks) of four different CO₂ sources, as computed based on multiple criteria except for proximity to sinks (which is to be considered later during joint ranking). Likewise, three CO₂ storage sinks are also evaluated and ranked as seen in the second column of Table 4, based on consideration of all criteria, except for proximity to sources (also to be considered at a later stage in the decision process).

Table 3: Normalized scores and ranks of CO₂ sources before and after consideration of sink proximity

<table>
<thead>
<tr>
<th>Source</th>
<th>Prior Scores and Ranks</th>
<th>Updated Scores and Ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.248 (2)</td>
<td>0.242 (3)</td>
</tr>
<tr>
<td>2</td>
<td>0.299 (1)</td>
<td>0.285 (1)</td>
</tr>
<tr>
<td>3</td>
<td>0.234 (3)</td>
<td>0.216 (4)</td>
</tr>
<tr>
<td>4</td>
<td>0.219 (4)</td>
<td>0.257 (2)</td>
</tr>
</tbody>
</table>

Table 4: Normalized scores and ranks of CO₂ sinks before and after consideration of source proximity

<table>
<thead>
<tr>
<th>Sink</th>
<th>Prior Scores and Ranks</th>
<th>Updated Scores and Ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.323 (2)</td>
<td>0.404 (1)</td>
</tr>
<tr>
<td>2</td>
<td>0.423 (1)</td>
<td>0.380 (2)</td>
</tr>
<tr>
<td>3</td>
<td>0.255 (3)</td>
<td>0.216 (3)</td>
</tr>
</tbody>
</table>
It can then be seen that these ranks need to be updated based on mutual interdependencies of the ranking order. The ANP framework allows the two-way dependency to be accounted for simultaneously, leading to updated scores and ranks of sources and sinks, as shown in the final columns of Tables 3 and 4, respectively. Note that the updated scores reveal a shift in the priority ranks of some of the alternative sources and sinks in the system. In other words, highly ranked sources tend to be in relatively close geographic proximity to highly ranked sinks, and vice-versa. For example, we can see the reversal of ranks of Sinks 1 and 2 in Table 4. This shift is due to the fact that Sink 1 is physically nearer to the highest ranked source (Source 2) as compared to Sink 2. The reversal thus reflects the effect of the geographic proximity criterion on the ranks. This effect is symmetrical; i.e., the shift in sink rankings also has a mutual effect on the source ranks, as shown in Table 3.

5. Conclusions
An analytic network process (ANP) approach to the joint ranking of CO₂ sources and sinks in carbon capture and storage (CCS) systems has been developed. This approach is able to account for feedback loops that exist in the interdependent preference ranks of sources and sinks, which results from the use of mutual geographic proximity as an important criterion for evaluating the decision elements. A hypothetical but realistic case study has been solved to illustrate this approach. The methodology may be readily extended in future work by applying it to real case studies; in addition, it may also be used for the related problem of joint ranking of specific classes of CCS technologies (as opposed to actual sites). The latter problem will be dealt with in our future work.

Acknowledgement
J. F. D. Tapia would like to thank the Philippine Department of Science and Technology (DOST) for providing research funding through the Engineering Research and Development for Technology (ERDT) program.

References