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Design of CO_2 Enhanced Oil Recovery Systems with Geological Sequestration as a Strip Packing Problem

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ABSTRACT

Carbon capture and storage (CCS) is an important technology that reduces CO_2 emissions and allows the use of power plants running in fossil fuels. It involves capturing CO_2 directly or indirectly from the flue gas and storing it to geological reservoir permanently. Injecting the captured CO_2 to a depleted oil reservoir can generate additional revenue through enhanced oil recovery (EOR) and at the same time, reduce CO_2 emissions. Scheduling of different operations given the required flow rate is necessary in order to maximize profitability. In this study, a continuous-time optimization model for designing enhanced oil recovery systems with geological sequestration is developed using the analogy of the strip packing problem. A case study is provided to illustrate the model.

KEYWORDS: Strip Packing Problem; Optimization; Enhanced Oil Recovery; Carbon Capture and Storage

1 INTRODUCTION

Carbon capture and storage (CCS) is an important technology for reducing industrial carbon dioxide (CO2) emissions which involves (Davison et al, 2001). Different storage techniques such as storage to saline aquifers, unminable coal seams and depleted oil reservoirs are used to prevent CO_2 emissions by injecting it in these reservoirs. However, the most developed technique used is injecting into depleted oil reservoir through enhanced oil recovery (EOR) in which 5 out of the 8 CCS in operation stage are in CCS-EOR (Global CCS Institute, 2012). With both generation of oil revenue and carbon credits can take place in EOR systems, it is necessary to optimally design and schedule EOR operations from a single source to multiple oil reservoirs. An effective pipeline design and schedule should be made to minimize the cost on of pipeline infrastructure from a source.

Several models for have been developed to address EOR operations with geological sequestration and schedule source-sink connections in CCS. Various models have been developed for CCS source-sink matching with sequestration scheduling have been developed using both discrete (Tan et. al, 2013) and continuous-time (Tan et al., 2012; Lee and Chen, 2012) approaches while a unified approach for both power generation losses and source-sink matching has been proposed (Lee et al., 2014). For EOR, Jahangiri and Zhang (2012) developed an ensemble based co-optimization approach considering the net present value of an operation. Leach et al. (2012) developed a dynamic co-optimization approach that determines the amount of CO_2 injected at a particular period. Huang et al. (2014) developed a scheduling approach for enhanced coal bed methane. These models however, either only addressed CCS source-sink matching problems or CO_2-EOR optimization with single source and single oil reservoir. In this study, the design and scheduling of CCS-EOR system with single source and multiple oil reservoirs is addressed as a strip packing problem. The strip packing problem involves placing different rectangular objects into a strip of definite width and infinite height (Riff et al., 2009). Defining the strip's and objects' dimensions can represent important scheduling problems such as the one addressed in this study.

The rest of the paper is organized as follows: Section 2 defines the problem statement while Section 3 gives the optimization model based on strip packing problem. Section 4 shows a simple case study and lastly, Section 5 shows the conclusions and future works.

2 PROBLEM STATEMENT

The formal problem statement addressed in this paper is as follows:

- The system consists of *m* depleted oil reservoirs and one CO_2 source.
- In this study, the CO_2 source operates for *T* years. In strip-packing, the operating life of the CO_2 source is considered the width, *(PH)* of the strip of infinite length.
- The injection to each reservoir yields an amount of oil equal to $(OR)_i$. The price of oil recovered is fixed at *(OP)*. Each operation can also start between the earliest time $(T_i)^e$ and the latest time $(T_i)^l$ and has a fixed duration of $(\Delta T)_i$.
- The amount of CO_2 stored for each reservoir is defined as S_i, of the CO_2 injected is sequestered. The amount of CO_2 stored is credited by $\$C^*$ per Mt CO_2 stored.
- The cost of transporting and injecting CO_2 to the reservoir is estimated using a linear cost function with a fixed cost component of $(C_o)^{pp}$ and variable cost component of $(C)^{pp}$. The variable cost component is proportional to the flow rate to the reservoir and the distance of the reservoir to the source.
- It is assumed that the common pipeline and the individual pipeline distances are predetermined based on the geographical and geological conditions while the sizes are determined based on the flow rates of the operation.

3 OPTIMIZATION MODEL

The objective function is to maximize the profit generated based from the total CO_2 credits and the oil recovered:

$$max\, PROF = OILREV + CARBCRED - TOTALCOST \quad (1)$$

Subject to:

$$OILREV = \sum_i (OP_i)(OR_i)\,(\Delta T_i^s)(f_i) \quad (2)$$

$$CARBCRED = \sum_i (CC)(SP_i)(\Delta T_i^s)(f_i) \quad (3)$$

$$TOTALCOST = COMMONPIPE + INDIVPIPE \quad (4)$$

$$COMMONPIPE = (Fx) + (D)(H) \quad (5)$$
$$INDIVPIPE = \sum_i [Fx + (Vc)(D_i)(f_i)] \quad (6)$$

where *(OILREV)*, *(CARBCRED)* and *(TOTALCOST)* are the oil revenue generated, carbon credits obtained from storage and the total costs for infrastructures in all the operations. The oil revenue generated is based on the oil yield, *(OR_i)* and the oil value *(OP_i)* for each reservoir while the carbon credits is based on the sequestration parameter SP_i . The total cost in this model is based only on the pipeline infrastructures: one would be on the common pipeline. The pipeline structure is based on two parts: the common pipeline *(COMMONPIPE)* and the individual pipelines *(INDIVPIPE)* which will meet on a common point. The cost function is a linear function with a fixed cost and a variable cost proportional to the flow rate requirement and the pipeline length. Also the common pipeline is based on the overall height of the strip used. The design of the EOR infrastructure is based on these constraints while the scheduling will strongly be based on the strip packing approach.

The positioning variables in the strip packing approach are shown as follows:

$$\frac{1}{2}(\Delta T_i + \Delta T_{i'}) \leq x_i - x_{i'} + PH(P_{i,i'} + Q_{i,i'}) \quad \forall i \ \ \forall i' \ i' > i \quad (7)$$
$$\frac{1}{2}(\Delta T_i + \Delta T_{i'}) \leq x_{i'} - x_i + PH(1 + P_{i,i'} - Q_{i,i'}) \quad \forall i \ \ \forall i' \ i' > i \quad (8)$$
$$\frac{1}{2}(f_i + f_{i'}) \leq y_i - y_{i'} + M(1 - P_{i,i'} + Q_{i,i'}) \quad \forall i \ \ \forall i' \ i' > i \quad (9)$$
$$\frac{1}{2}(f_i + f_{i'}) \leq y_{i'} - y_i + M(2 - P_{i,i'} - Q_{i,i'}) \quad \forall i \ \ \forall i' \ i' > i \quad (10)$$

For Eq. 7-10, the x-axis is represented by the length of EOR operation while the y-axis is the flow rate requirement. The coordinates shown in the model are the coordinates of the center of the boxes in the strip. These equations, based on Castro and Grossmann's continuous strip packing approach (2012), ensure that no rectangles overlap. In this system, the strip packing method allows the determination of the maximum flow rate requirement for the common pipeline which is only possible by using the strip packing approach.

The boundaries for x_i are based on scheduling constraints in which for every object, its rightmost side should be located on a specific boundary:

$$x_i \geq \frac{1}{2}\Delta T_i \quad \forall i \quad (11)$$
$$x_i \leq PH - \frac{1}{2}\Delta T_i \quad \forall i \quad (12)$$
$$x_i - \frac{1}{2}\Delta T_i \geq T_i^{early} \ \ \forall i \quad (13)$$
$$x_i - \frac{1}{2}\Delta T_i \leq T_i^{late} \ \ \forall i \quad (14)$$
$$y_i \leq H - \frac{1}{2}f_i \quad \forall \mathrm{i} \quad (15)$$
$$f_i = F_i b_i \ \ \forall i \quad (16)$$
$$\Delta T_i = \Delta T_i^s b_i \ \ \forall i \quad (17)$$

Equations 11-14 denotes the range at which x_i can placed and it implies that the operation can only start between the earliest time, T_i^{early} and the latest time, T_i^{late}. Equation 15 limits the boundary of the y-axis and Equations 16 and17 selects which operation should be done based on the economics of the operation.

The model is tested using a case study in Lingo 14.0 in a PC with 2.40 GHz processor and 4.00 Gb RAM. In this case, the time required to determine the optimal solution is negligible.

4 CASE STUDY

Four reservoirs are assumed to be connected to a source which operates at 30 years in the planning horizon (strip width). Table 1 shows the data for the oil reservoirs while Table 2 shows the parameters required to assess the economics of the entire EOR system.

Table 1: Reservoir Data for the Case Study

	Sink 1	Sink 2	Sink 3	Sink 4
Earliest Start of Operation, T_i^{early}, y	0	0	0	0
Latest Start of Operation, T_i^{late}, y	5	7	15	10
Flow Rate Requirement, F_i	2.4	3.0	1.5	2.5
Oil Recovery, $OR_{i,}$ million bbls/Mt	10	4	8	5
Sequestration Parameter, S_i	0.95	0.85	0.90	0.95
Operating Life for EOR, ΔT, y	10	15	20	10
Distance from the common point (km)	100	200	150	150

Table 2: Cost Data for Case Study

	Value
Length of Planning Horizon, y	30
Oil Price, $/barrel	70
Carbon Credit, $/Mt	23
Fixed cost, million$	20
Variable Cost, million$/Mt-km	0.01
Common Pipeline Distance	150

Using, the model the optimal solution is shown in Figure 1 illustrating the optimal schedule as the operations are packed in a strip and Figure 2 illustrating the pipeline network.

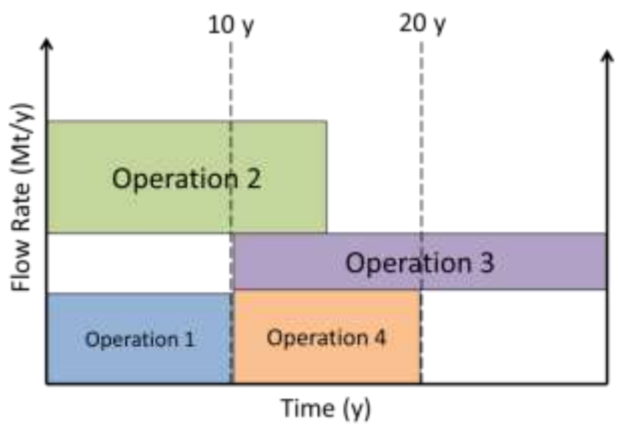

Figure 1: Strip Packing Solution for the Case Study

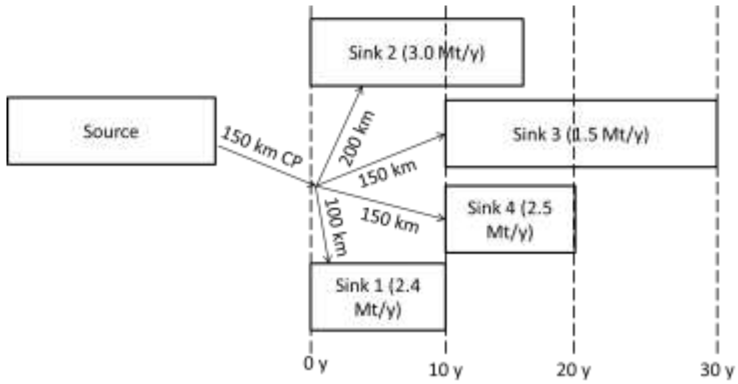

Figure 2: Pipeline Design and Operation Schedule for the Case Study

The total profit generated is equal to US$57.4 billion which 97% comes from the oil revenue. As shown, Operations 3 and 4 should start after 10 years, while Operations 1 and 2 start at the start of the planning horizon. With these scheduling, the maximum flow rate is equal to 7 Mt/ y which will be delivered using a 150-km common pipeline. Table 3 summarizes the economics of the EOR system.

Table 3: Economic Result for EOR Case Study

Cost Parameter	**Value (M$)**
Profit	57,396
Oil Revenue	54,950
Carbon Credits	2571.40
Costs	30.50 (common pipeline)
	94.40

5 CONCLUSION AND FUTURE WORK

The design of CO_2 enhanced oil recovery (EOR) system as a strip packing problem was addressed using a linear program (LP) developed. The scheduling of the EOR system was done by positioning the operations as rectangles in a strip representing the strip with definite length (planning horizon) and infinite height (flow rate supply). The design of the common pipeline was based on the maximum height used in the strip and combining these yielded a linear program addressing both design and scheduling problems.

Future works including addressing the issue in the CO_2 supply side rather than the CO_2 sink side and to address the uncertainties such as oil prices and oil reservoir parameters.

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