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Design and Scheduling of CO_2 Enhanced Oil Recovery with Geological Sequestration Operations as a Strip Packing Problem

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Carbon capture and storage (CCS) is an important technology that enables the reduction of CO_2 emissions while allowing the use of power plants running in fossil fuels. Coupled with enhanced oil recovery (EOR), it allows additional revenues to be realized by increased oil production through the injection of captured CO_2 into depleted oil reservoirs. For a system with multiple reservoirs, it is necessary to determine the amount of CO_2 to be supplied and the schedule of EOR operations to be conducted. This also requires the optimal design and scheduling of each operation to maximize profitability. In this study, a mixed integer linear program (MILP) was developed using the analogy of the strip packing problem. A case study is presented to illustrate the model.

1. Introduction

Carbon capture and storage (CCS) is an important technology for reducing industrial carbon dioxide (CO_2) emissions. It involves removing potential CO_2 emissions from flue gas, transporting through pipelines and storing it into geological reservoirs for permanent storage (Davison et al, 2001). The most mature technique for permanently storing CO_2 is the injection into depleted oil reservoirs for enhanced oil recovery (EOR), which could provide initial momentum for further large-scale CCS deployment. According to the current worldwide status of CCS, 25 % of the CCS operations in the world are in the operation stage, and 63% of them are applied for EOR operations (Global CCS Institute, 2012). Coupling CO_2 sequestration with EOR could provide long term storage potential in a particular CO_2 sink benefiting the environment; whilst serving as a business driver to oil companies on improving oil recovery.CCS operations are highly dependent on the 3 critical success factors on CO_2 capture, CO_2 transport and CO_2 storage. Both CO_2 capture and CO_2 storage involves technology selection, R&D maturation and large scale deployment which is widely discussed today as compared to CO_2 transport. CO_2 transport revolves around transporting the captured CO_2 to the storage sites, typically via pipeline networks.However, an effective pipeline network should be synthesized to minimize the cost of pipeline infrastructure, and to minimize the required CO_2 supply to execute EOR operations. This would require the proper scheduling of each operation to minimize the annual CO_2 requirement.
Various models for CCS source-sink matching with sequestration scheduling have been developed using both discrete-time (Tan et al., 2013), continuous-time (Tan et al., 2012) and simplified continuous-time (Lee and Chen, 2012) approaches, while a unified approach considering both power generation losses and source-sink matching has been proposed (Lee et al., 2014). Addressing uncertainties to manage storage risks using fuzzy optimization (Tapia and Tan, 2014) and new information to modify the existing network using optimal revamp (Tapia and Tan, 2015) have been addressed in previous papers. Cormos and Simon (2013) developed a dynamic model for CO_2 capture utilizing-calcium looping cycle. Also, several

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approaches have been proposed to optimize EOR operations; for example, Jahangiri and Zhang (2012) and Leach et al. (2011) both addressed the economic viability of operations. These studies, however, only address the economics of CCS alone, or CCS in combination with EOR, but lack consideration to optimized scheduling of each oil reservoir. This aspect can be useful for minimizing the annual CO_2 requirement for the entire planning horizon.
This paper demonstrates that the scheduling and design of EOR operations can be represented as a strip packing problem (Riff et al., 2009), since its economic and temporal parameters can be represented in the components of strip packing. In the context of this study, the strip represents the CO_2 source of definite planning horizon (strip width) and the packing objects represents the EOR operations with definite flow rate requirement (object height) and definite operation length (object width). The design and scheduling of EOR operations for multiple oil reservoirs has not yet been made. In this study, this problem has been addressed in this paper as a strip packing problem. The rest of the paper is organized as follows: Section 2 discusses the problem statement while Section 3 shows the optimization model based on the strip packing problem. Section 4 illustrates the model using a simple case study. 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 single CO_2 source.
- In this study, the CO_2 source operates for T years. In strip-packing, the planning horizon scheduled for the CO_2 source is considered the strip width, (PH) of the strip of infinite height. It is assumed that the CO_2 source can supply all operations' CO_2 requirement, but the annual CO_2 supply incurs costs for the design of the pipeline infrastructure.Note that the other cost elements related to CO_2 capture (e.g membrane, amine unit & etc) and compression for transport is not considered as a cost variable in this work.
- The injection to each reservoir yields an amount of oil equal to $(OR)_i$. The oil recovered can be sold at a price denoted by $(OP)_I$ depending on its value. Each operation can start between the earliest time $(T_i)^e$ and the latest time $(T_i)^l$. It has a fixed duration (object width) of $(\Delta T)_i$ and requires a flow rate (object height) equal to f_i.
- The amount of CO_2 stored in each reservoir is defined as S_i of the CO_2 injected. The amount of CO_2 stored is credited by \$C* per t CO_2 stored.The amount of CO_2 stored permanently is assumed to be traded in exchange for carbon credits (Roussanaly and Grimstad, 2014).
- The cost of transporting and injecting CO_2 to the reservoir is estimated using a linear cost function with a fixed cost component of $(Cf)_{pp}$ and a variable cost component of $(Cv)_{pp}$. The variable cost component is proportional to the flow rate to the reservoir and the distance of the reservoir from the source.
- For the pipeline infrastructure, a common pipeline is routed from the source up to a common point (typically an offshore platform/structure) and redistributed via individual pipelines branches from the common point to respective reservoirs. 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 CO_2 transported.

3. Optimization Model

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

$$\max PROF = OILREV + CARBCRED - TOTALCOST \tag{1}$$

Subject to:

$$OILREV = \sum_i [(OP)_i (OR)_i (\Delta T)_i (f_i)] \tag{2}$$

$$CARBCRED = \sum_i [(C^*)(S_i)(\Delta T)_i (f_i)] \tag{3}$$

$$TOTALCOST = COMMONPIPE + INDIVPIPE \tag{4}$$

$$COMMONPIPE = (Cf)_{pp} + (Cv)_{pp}(D)(H) \tag{5}$$

$$INDIVPIPE = \sum_i (Cf)_{pp} + (Cv)_{pp}(D_i)(f_i) \tag{6}$$

where (OILREV), (CARBCRED) and (TOTALCOST) are the oil revenue generated, carbon credits obtained from storage and the total costs for infrastructures, respectively, 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 $(S)_i$, which denotes how much CO_2 is stored permanently with respect to how much CO_2 is injected. The total cost in this model is based only on the pipeline infrastructure. The pipeline structure is based on two parts: the common pipeline (COMMONPIPE) and the individual pipelines (INDIVPIPE) for redistribution to the individual reservoirs. The cost function is assumed to be 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:

$$0.5[(\Delta T)_i + (\Delta T)_{i'}] \le x_i - x_{i'} + PH(P_{i,i'} + Q_{i,i'}) \qquad \forall i, \forall i, i', i > i \tag{7}$$

$$0.5[(\Delta T)_i + (\Delta T)_{i'}] \le x_{i'} - x_i + PH(1 + P_{i,i'} - Q_{i,i'}) \qquad \forall i, \forall i, i', i > i \tag{8}$$

$$0.5[f_i + f_{i'}] \le y_i - y_{i'} + M(1 - P_{i,i'} + Q_{i,i'}) \qquad \forall i, \forall i, i', i > i \tag{9}$$

$$0.5[f_i + f_{i'}] \le y_{i'} - y_i + M(2 - P_{i,i'} - Q_{i,i'}) \qquad \forall i, \forall i, i', i > i \tag{10}$$

For Eqs(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. $P_{i,i'}$ and $Q_{i,i'}$ are binary variables that determines the position of the object *i* with respect to object *i'*; $P_{i,i'}$ denotes which axis are taking in consideration while $Q_{i,i'}$ denotes whether the object is ahead or behind the other. These equations, based on Castro and Grossmann's (2012) continuous strip packing approach, 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 and y_i are based on scheduling constraints in which for every object, its rightmost side should be located on a specific boundary:

$$x_i \ge 0.5[(\Delta T)_i] \qquad \forall i \tag{11}$$

$$x_i \le PH - 0.5[(\Delta T)_i] \qquad \forall i \tag{12}$$

$$x_i - 0.5[(\Delta T)_i] \ge (T_i^e) \qquad \forall i \tag{13}$$

$$x_i - 0.5[(\Delta T)_i] \le (T_i^l) \qquad \forall i \tag{14}$$

$$y_{i'} \le H - 0.5 f_i \qquad \forall i \tag{15}$$

$$P_{i,i'} \in \{0,1\} \qquad \forall i, i' \tag{16}$$

$$Q_{i,i'} \in \{0,1\} \qquad \forall i, i' \tag{17}$$

Eqs (11)-(14) denotes the range at which x_i can be placed, implying that the operation can only start between the earliest specified time $(T_i)^e$ and the latest specified time $(T_i)^l$. 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 obtain the optimal solution is negligible.

4. Case Study

Four reservoirs are assumed to be connected to a source which operates at 30 y 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, $(T_i)^e$, y	0	0	0	0
Latest Start of Operation, $(T_i)^l$, 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, $(\Delta T)_i$, 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, $/barrel	70
Carbon Credit, M$/Mt	23
Fixed cost, million$	20
Variable Cost, million$/Mt-km	0.01
Common Pipeline Distance	150

Solving the model yields the optimal solution shown in Figures 1 and 2. Figure 1 illustrates the optimal schedule as the strip packing, and Figure 2 the pipeline network with a common pipeline and four individual pipelines. The flow rates for each operation are also indicated.

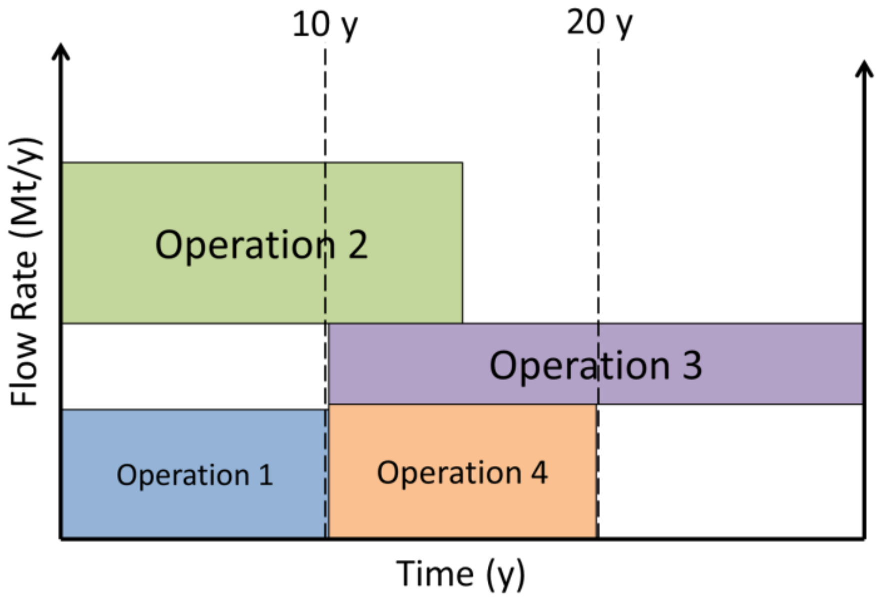

Figure 1: Strip Packing Solution for the Case Study

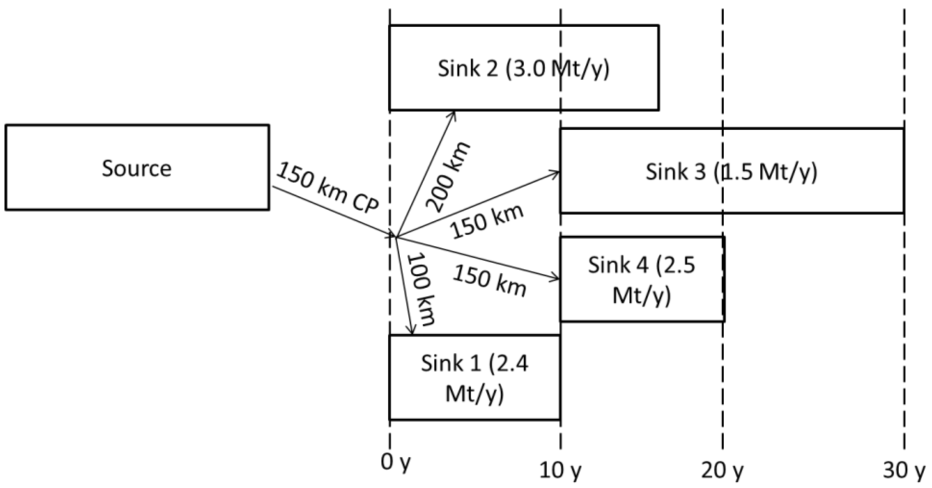

Figure 2: Pipeline Design and Operation Schedule for the Case Study

The total profit generated is equal to US$ 57.4 billion, 97 % of which comes from the oil revenue. As shown, Operations 3 and 4 should start after 10 years, while Operations 1 and 2 at the beginning of the planning horizon. With this schedule, the CO_2 flow rate from the source has a maximum of 7 Mt/y during 10-15 y, and is delivered using a 150 km common pipeline. As shown in Figure 2, the flow rate supplied by the source is 5.4 Mt/y for the first 10 y, 7 Mt/y up to 15 y, 4 Mt/y up to 20 y and 1.5 Mt/y up to 30 y. This shows that the capacity used for the common pipeline ranges from 21 % up to 100 %. If all operations overlap, the maximum total CO_2 flow rate required is equal to 9.4 Mt/y, which is 34 % greater than the minimum flow rate required (7 Mt/y). For the common pipeline design, the minimum flow rate that would occur is 1.5 Mt/y when only Operation 3 is active in the later stage of the planning horizon. The strip packing approach for this problem allows the minimization of the capacity required for the common pipeline by scheduling the different operations. Results from the strip packing approach can be translated into critical design decisions such as selecting the optimized pipeline size, compressor capacity or even deciding on the operations philosophy (timing of operation, well shut-in & etc) in EOR management. Table 3 summarizes the economic performance 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. Conclusions and Future Work

A strip packing problem-based optimization model for the design and scheduling of EOR operations with geological sequestration has been developed. The model aims to minimize the CO_2 supplied by the CO_2 source to meet the flow rate requirements of EOR operations. The model also aims to maximize the total profit based on CO_2 credits, oil recovery and the costs for the pipeline infrastructure with a common pipeline and individual pipelines for each reservoir. The strip packing approach is utilized to schedule EOR operations to minimize the total CO_2 flow rate from the source.

Future work includes the extension of the current model to consider uncertainties in the parameters such as oil and carbon prices, oil yield and storage capacity and to consider multiple CO_2 sources with various profit allocation schemes.

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