Selecting The Optimal Ranking Strategy and Scheduling of Eor Processes in an Oil Field Through Stochastic Mixed Integer Programing

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Abstract

Enhanced Oil Recovery with their application methods in an oil field increases the recovery. The additional recovery of oil is made possible economically from advances in technology. The scheduling and planning must be taken in consideration in rapid time for the lifespan of a of a project of an oil reservoir

Demands for oil are growing up rapidly specially in countries in development (including even China and India). Declining oilfield productivity on the other side is taking place rapidly. Experience for these methods and technics yield that they are very complex. Improving the profits or the overall cumulative oil production can be obtained only if there is an optimal planning and scheduling from the beginning of the development oil field. The optimal result can be obtained if only we know from the beginning of the life of reservoirs. A crucial point is that we must know the duration of each of them and the time period or interval these EOR technics must be applied. We need to do the computer simulations, after the problem is conceptualized, to perform the right hierarchy selection procedure. Sometime it happens that we may have not chosen the right selection strategy from the beginning, giving rise to non-optimal profitable EOR methods. We must be able in these conditions to reallocate the problem again, and run again and again the stochastic simulations in computer. To perform all these activities, there exists no mathematical algorithm in space and time, so we have to choose the right method for the oil reservoir, that might be different for another oil reservoir. To choose the proper hierarchy and scheduling for a certain oil field is challenge in itself. In this work we will make use of stochastic mixed integer programing to address this complex and challenge problem.

Key words: Enhanced Oil Recovery; optimal hierarchy and scheduling of EOR; stochastic computer simulations; stochastic mixed integer programing

1.Introduction

Until now, to our best knowledge, it has been impossible to find a determined or stochastic strategy that can maximize the profit or the value of NPV for the lifetime of an oil reservoir while taking in consideration the Enhanced Oil Recovered techniques. Large number of parameters of reservoir change, most of them do it continuously just under a single determined EOR. Meanwhile it is hard to know the time interval we will inject and how the different parameters of reservoirs like permeability, porosity, saturation, etc. will change with time. The strategy to begin with is poorly known or uncertain because there are several of them to take in consideration; steam injection, water injection, CO_2 injection, polymer, surfactant, solvents, bacteria injection etc. To make the problem more complicated, another source of uncertainty is that we don't know with certainty the selection of series of wells we have to inject and the producers' locations, the number of them, etc. So, it is practically impossible to maximize the expected Net Present Value finding so a time series for the switching regimes. Several papers deal with this problem. There is no definite solution yet despite the fact that there are many articles for this problem. We will try to give some aspects, without pretending to find the optimal strategy definitely. Solving the optimal makespan of a project (in our case the set of EOR techniques) can be regarded as an application of real options theory (see Dixit and Pindyck (2004), Trigeoris (2016).

By agreement in our work, we will call each of the EOR techniques an activity. The most used EOR technics used today are; Water injection, CO_2 injection, solvent injection, steam injection, polymer injection, surfactant injection, ASP injection, in situ combustion, thermal methods, SAGD, microbial methods, water alternating gas, Low-Salinity Waterflooding and CO_2 Low-Salinity WAG. None of this technics or method has the status of the preferred EOR method. But there are some indications for the candidate wells for EOR implementation like; high values of the remaining recoverable oil, low water cut, history of water and polymers injection and others. Studding the various aspect of different technics of EOR processes and decision-making has been part of a lot of work. P.R. King (2015), Stanford, studied for flexibility and decision making in surfactant flooding and time when to begin this process, that is one of the first work in this contest. Costa et al. (2008), to evaluate the impact of uncertainty introduced a method related to chemical flooding and used for chemical injection representative models in decision-making.

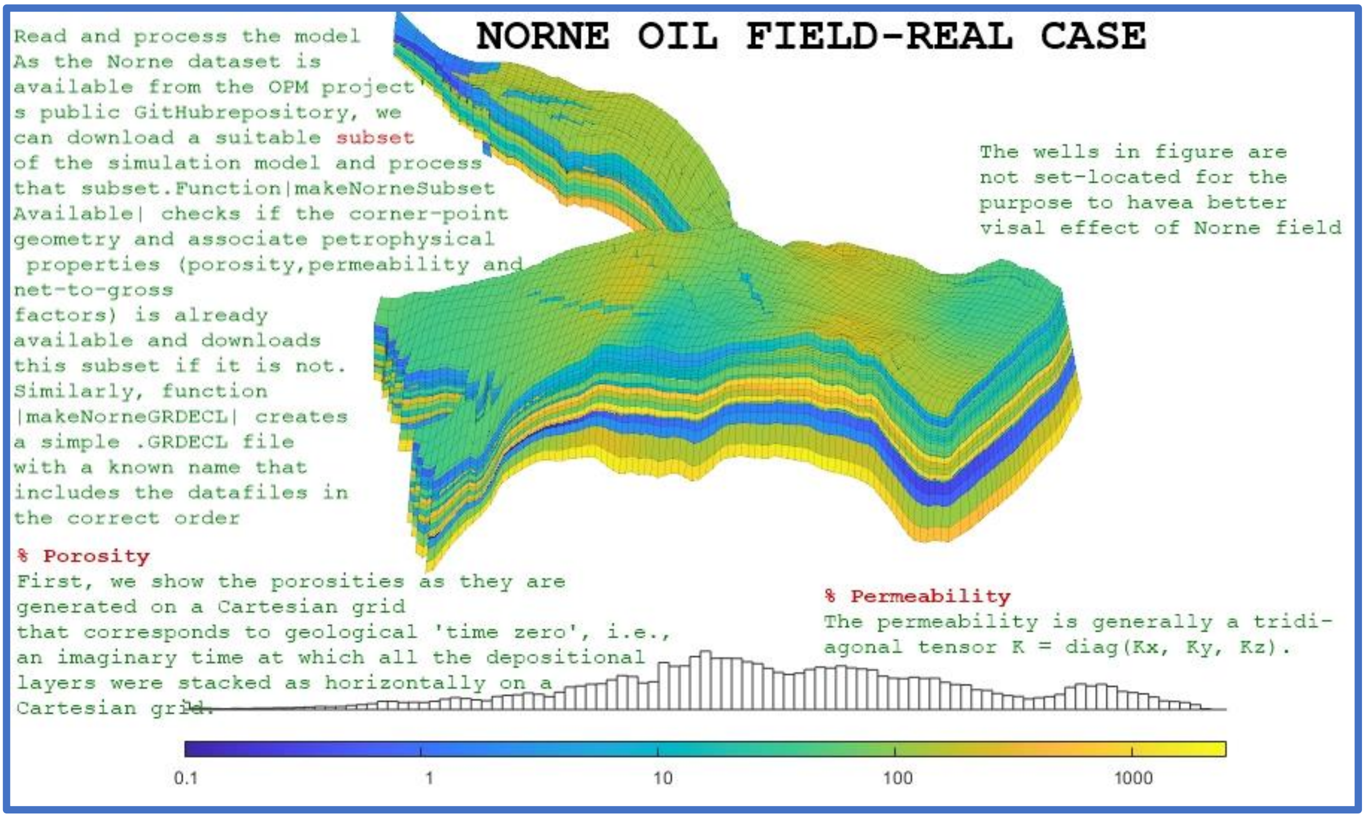


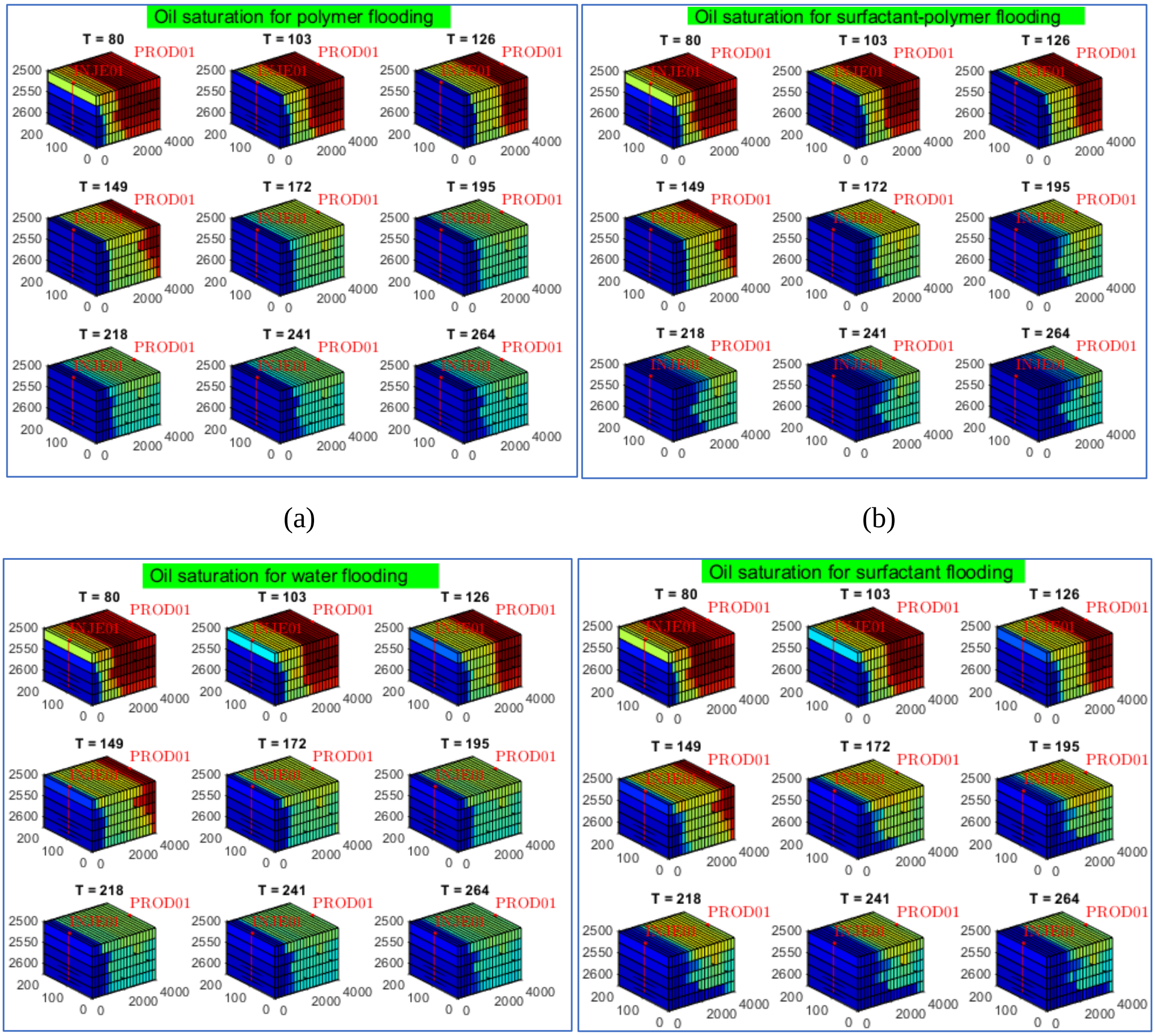
Figure 1. The oil reservoir under consideration is the Norne Field in the North Sea, with active and inactive cells and with real data, located between Norway and England. Figures below are only a part of reservoir. This is done for reducing the calculation time. If we would take in consideration the entire reservoir the overall time would be 3-4 hours. This time is relatively high because depends from the tolerance, algorithm, computer, number of iterations. In this case, giving a large enough number of iterations would ensure that we have found the global optimum (1 solution) and not the local optimum (several solution). The well-known Genetic Algorithm (**Holland, Harward, 1975**) is not recommended in this case because the high number of chromosomes to be used for the optimization.

Table 1-Screening criteria for EOR processes. With blue color the 4 agents that will be used recursively for the strategy because they meet the screening criteria to be used for the oil field SPE10 (layer 35)

EOR process	Density [^{0}API]	Viscosity [mPa s]	Oil Saturation [%]	Formation type	Net thickness [m]	Permea-bility [10^{-15} m^2]	Depth [m]	Tempe-rature [^{0} C]
Chemical								
Polymer	>25	5-125	>10	Preferable sandstone	NC	>20	<2700	<90
Surfactant-polymer	>15	20-30	>30	Preferable sandstone	>3	>20	<2700	<90
Surfactant	13-35	<200	>10	Preferable sandstone	NC	>20	<2700	<90
Miscible gas injection								
Hydrocarbon gas	>35	<10	>30	Sandstone or carbonate	5-7.5	NC	>1350	NC
CO_2	>25	<12	>30	Sandstone or carbonate	5-7.5	NC	>600	NC
solvent	>35	<10	>30	Sandstone or carbonate	5-7.5	NC	>1350	NC
Water injection								
Water injection	>25	<10	>25	Sandstone or carbonate	3.5-5.5	NC	>1350	NC
Water alternating gas	>20	<12	>20	Sandstone or carbonate	3.5-5.5	NC	>400	NC

2. Anticipated case study and the necessity to have a mathematical model.

We will denote a EOR project to be composed by several activities, that are exactly the methods used for EOR processes. The processes that will take in consideration are given in table 1, column 1. This table with the screening criteria is taken from different oil field development projects in the word from expert's guide. There are other different screening criteria for other oil fields of the expert's guide justifying the fact that until now does not exist a unified, unique guide. The candidate activities in our case are: polymer flooding, surfactant-polymer flooding, water flooding and surfactant flooding. In the figure (1) bellow are given the four cases of oil saturation for the SPE10 case, taken from the execution of MRST-SINTEF software. The time of simulation for four different cases is 30 years and from figures correspond to T=264.



(a) (b)

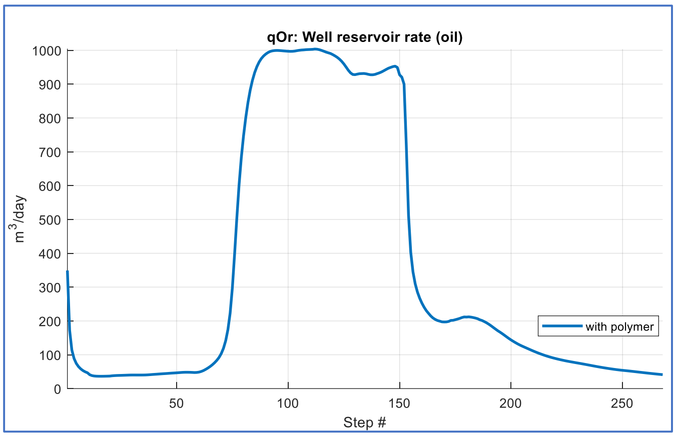
(c) (d)

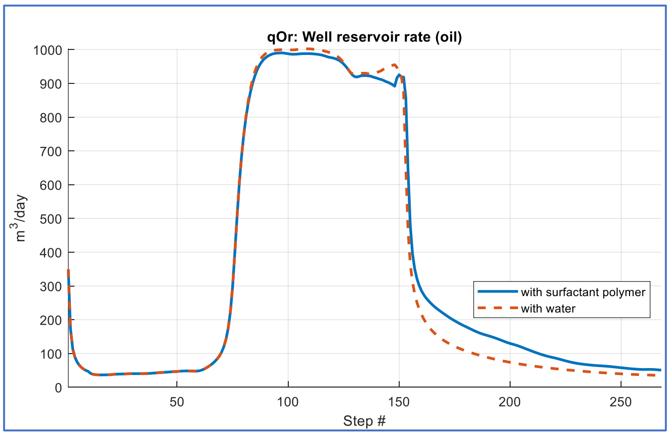
Figure 2. (a) Oil saturation for polymer flooding, (b) Oil saturation for surfactant-polymer flooding, (c) Oil saturation for water flooding, (d) Oil saturation for surfactant flooding. (D.Zeqiraj-MRST MATLAB)

The makespan of the project is 30 years with the goal maximizing the NPV. The questions that arise are:

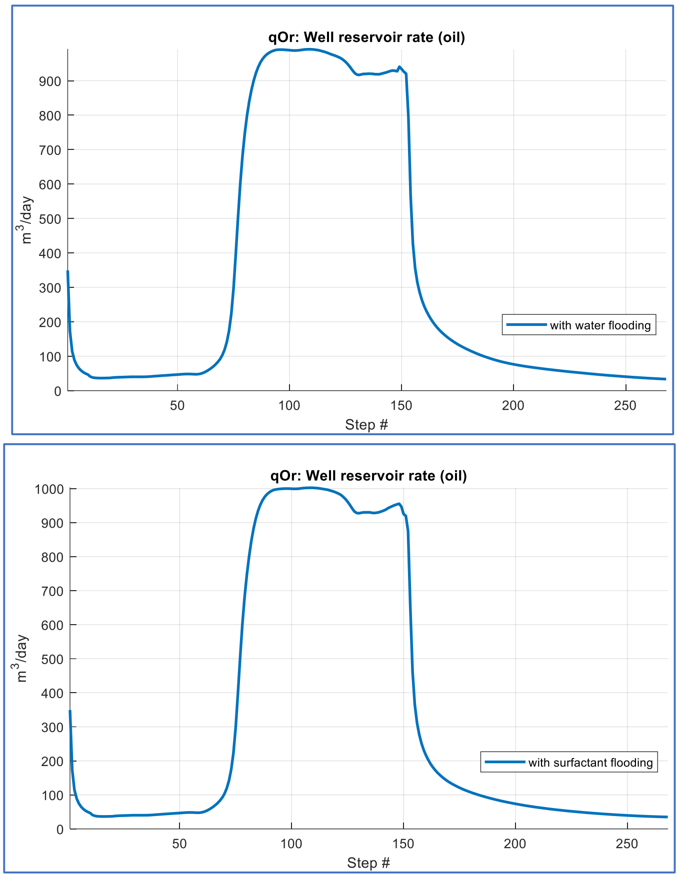
1. What would be the value of NPV for different combinations of 4 injecting agents?

2. At what time should the injection of candidate agents start and whether in this case we would have a maximum NPV?
It is clear that we must strictly adhere to the screening criteria (table 1) for any possible combination that gives us maximizing NPV. Of course, the most difficult problem is when to start an activity or alternative and how long should take its process. So, it is clear that to address these problems we must turn to methods of optimization of a stochastic nature. The latter is of stochastic nature not only for the uncertainty of the parameters but also for the duration of a single method, so the beginning and the end are uncertain.





(a) (b)



(c) (d)

Figure 3. Corresponding graphs to figure 1: (a) Well reservoir rate (oil) with polymer, (b) Well reservoir rate (oil) with surfactant-polymer and with water (separated, yellow curve), (c) Well reservoir rate (oil) with water, (d) Well reservoir rate (oil) with surfactant flooding. The model of flow is three phase black-oil. The entire time-step in x-axes correspond to 30 years of simulation. (D.Zeqiraj-MRST MATLAB)

3. Mathematical Model

The model we have chosen is taken from [28] and is a mixed integer stochastic nonlinear programing. The stochastic nature derives from the fact of uncertain duration of a certain activity-method EOR and the stochastic constraints

3.1. Variable of Decision of Problem

$x_{it} = \begin{cases} 1 & \text{if at time t is completed the selected activity i} \\ 0 & \text{otherwise} \end{cases}$; $y_i = \begin{cases} 1 & \text{if is selected activity i} \\ 0 & \text{otherwise} \end{cases}$

3.2. Indices and Parameters

Below are given the Indices:

i, j: are the indices of any activity i = 1, . . ., N; j = 1, . . ., N
k: are the indices of intervals k = 1, …, D_i
t: are the indices of time t = 1, …, T

Below are given the parameters:

D_i: duration of activity i
ir: rate of interest.
T: makespan of 4 activities or the entire EOR project.
N: the number of activities that are good candidate.
S: activities with a set of relations (precedence) between them
U: set of activities that can be repeatable
g_{ij}: the overlap or separation determining the number of periods between activities i and j
τ_{ij}: dependency of cost through activity i and j.
F_{ik}: normal random variable 'earnings for activity i in period k ($k \in \{0, 1, \ldots, Di\}$).
$E(F_{ik})$: earnings expected value for activity i in period k ($k \in \{0, 1, \ldots, Di\}$).
C_i: cost of investment for activity i as a random normal variable
$E(C_i)$: cost of investment as an expected value for activity i.
R_t: budget in time t given as a random normal variable
α: maximum risk acceptable for spending more than R_t.

3.3. Formulation

$$\max Z_1 = \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{k=1}^{D_i} \frac{E(F_{ik}).x_{i(t+D_i-k)}}{(1+ir)^t} - \sum_{i=1}^{N}\sum_{t=1}^{T} \frac{E(c_i).x_{it}}{(1+ir)^{t-D_i}} \times \prod_{j=1}^{n}\left(1-\tau_{ij}\times y_j\right) \quad (1)$$

$$\min Z_2 = \mathrm{var}\left(\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{k=1}^{D_i} \frac{F_{ik}x_{i(t+D_i-k)}}{(1+ir)^t}\right) \quad (2)$$

$$p\left(\sum_{i=1}^{N} c_i . x_{i(t+D_i)} \prod_{j=1}^{n} \left(1 - \tau_{ij} \times y_j\right) \geq R_t\right) \leq \alpha \qquad \forall t = 0,1,2,\ldots,T \qquad (3)$$

$$\sum_{t=1}^{T} x_{it} \leq y_i \qquad \forall i = 1,2,\ldots,N \qquad (4)$$

$$\sum_{t=1}^{T} (t - D_i) . x_{it} \leq 0 \qquad \forall i = 1,2,\ldots,N \qquad (5)$$

$$\sum_{t=1}^{T} x_{jt} . \left(\sum_{t=1}^{T} (t + g_{ij}) . x_{it}\right) \leq \sum_{t=1}^{T} (t - D_j) . x_{jt}; \qquad \forall (i,j) \in S(i,j) \qquad (6)$$

$$\sum_{t=1}^{T} x_{it} \geq \sum_{t=1}^{T} x_{jt} \qquad \forall (i,j) \in S(i,j) \qquad (7)$$

$$x_{ij} \in \{0,1\}; \quad y_i \in \{0,1\}; \qquad \forall\, i,j,t \qquad (8)$$

In above formulation there are two objective functions. The first objective functions Equation (1) has two terms. The first term is the NPV of sum of activity's earnings. The second term considering other activities is expectation of (NPV) activity's cost sum. The minimization of variance stands for the second objective function. Constrain 3 stands for limiting the probability of expenditure not surpass α. Constraints (4) and (5) yields that if an activity is selected it may be not necessary completed within a given lifespan because it may result not feasible economically. So, this activity gets abandon and the next activity begin. Constraints (6) and (7) indicate the mode of modeling the precedence relations. Constraint (8) stand for the decision variables.

4. Solution of the proposed mathematical model with the software PYOMO in Python (stochastic mixed integer nonlinear programing)

The formulation of mathematical model (3) is a stochastic mixed integer nonlinear programing with stochastic constraints and can be solved in a variety software way including

- **PYOMO in Python**
- GENETIC ALGORITHM
- CPLEX
- GORUBI

In this work we will make use of **PYOMO** software which can be found on GitHub: https://github.com/Pyomo/pyomo.git for solving the formulation (3).

5. Case study. Formulation of the dual problem using PYOMO software and MRST-SINTEF

Looking in table 1 we will make use of 4 injection agents (colored with blue). In a simple way, taking in consideration the above formulation our problem reads:

Select the optimal ranking strategy and scheduling for 4 injected agents that maximize the overall expression 1 and minimize expression 2 to formulation 3.3

The oil field in this case study is the SPE10, layer 35. There are 4 candidate injection agents with data in table 1. In table (2) are given agent injection names, annual earnings with the normal distribution (with mean and standard deviation), investment costs, standard activity’s lifespan and precedence relationship which means that an activity begin when the predecessor has finished (called Finish-to-Starts, FS)

Table 2 Project's Data

Row	Agent injection name (candidate)	Annual earning (million $)	Investments Costs (million $)	Activity's lifespan (year)	Precedence relation
1	Polymer injection	N (50,5)	N (50,5)	7.5	------
2	Polymer-surfactant injection	N (45,5)	N (40,4)	7.5	FS_{12}(-4)
3	Surfactant injection	N (30,5)	N (40,5)	7.5	FS_{15}(-2)
4	Water injection	N (35,5)	N (50,5)	7.5	FS_{16}(-3)

In table 3 is given cost dependency of activity *i* and *j*. A typical cost of dependency is the project 6, WAG - water alternating gas. Other cost dependences are the projects 2 and 5.

Table 3: Cost dependency of our injection agents (activity)

Activity	1	2	3	4
1	0.55	0.60	0.50	0.70
2	0.60	0.45	0.40	0.55
3	0.50	0.40	0.60	0.65
4	0.70	0.50	0.45	0.60

After solving the above algorithm in PYTHON, we find the following sequence of optimal EOR scheduling processes. Now we are ready for the final solution doing the calculations like below. In table 4 we are given the hierarchy (from programing) of the projects, and the duration of each of them

Table 4: Final solution of the problem

Ranking of the 4 activities	Activity	De facto duration of each activity in years
1	Water injection	6.01
2	Polymer injection	5.22
3	Surfactant injection	6.89
4	Surfactant-polymer injection	6.24

Discussion

Initially each activity's lifespan was 7.5 years, so the makespan forecasted was 7.5*4=30 years. De facto from table 4 the total duration of entire project is: Sum (T) = 6.01+5.22+6.89+6.24= 24.36 years; so, there is a difference of 5.64 years less than forecasted. This happened because of parameter $\mathbf{g_{ij}}$

Example

The example bellow, illustrated graphically, is taken from MRST software and the results are compared with ECLIPSE software, being in complete compatibility between them. The fact is that the selecting hierarchy matches the results obtained from our mathematical modeling (see table 4, second column). Regarding the time difference that according to MRST-ECLIPSE is 30 years and that in our case the makespan of the project is 24.36 years we are of the opinion that at this point the problem becomes really challenging and to be studied with many other cases. Probably because the screening criteria for EOR processes in the case of this paper and that taken from the example of MRST-ECLIPSE may differ slightly. Finally, the mathematical model that we have chosen as every mathematical model that never represents the full reality, cannot be perfect.

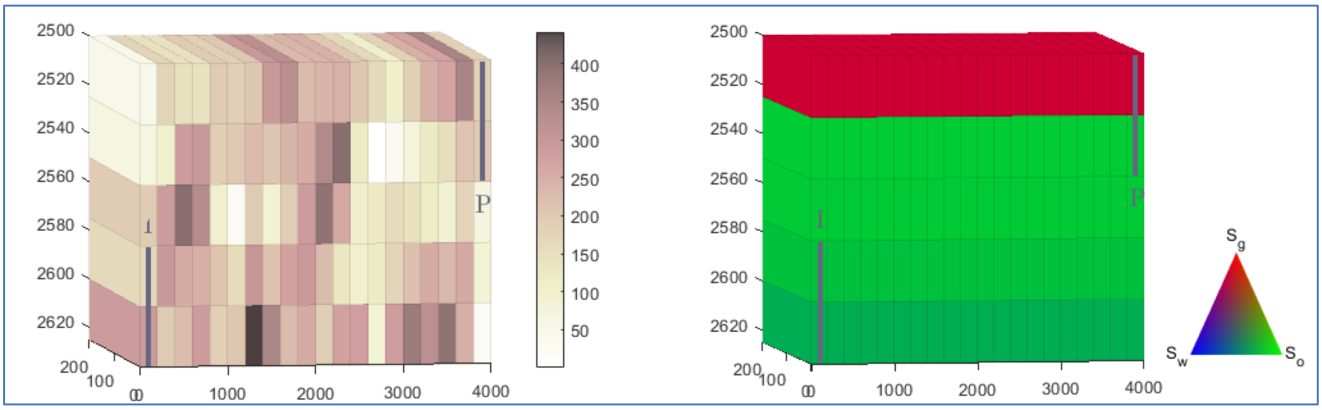


Figure 4. Example of injection of our 4 agents in the bottom of reservoir, production in the upper part. 1260 days water preflush; follow chemical slug 1700 day; washed out by 8000 days. (D.Zeqiraj**)**

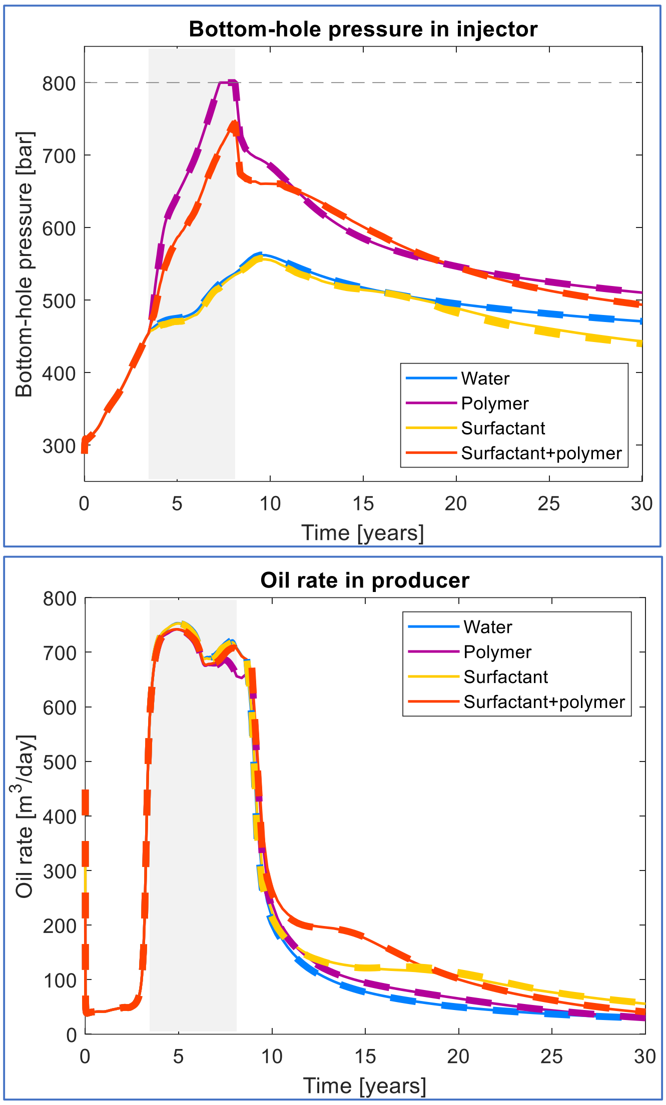


Figure 5. In the left bottom hole pressure of inj. well, on right oil rate in producer. (D.Zeqiraj)

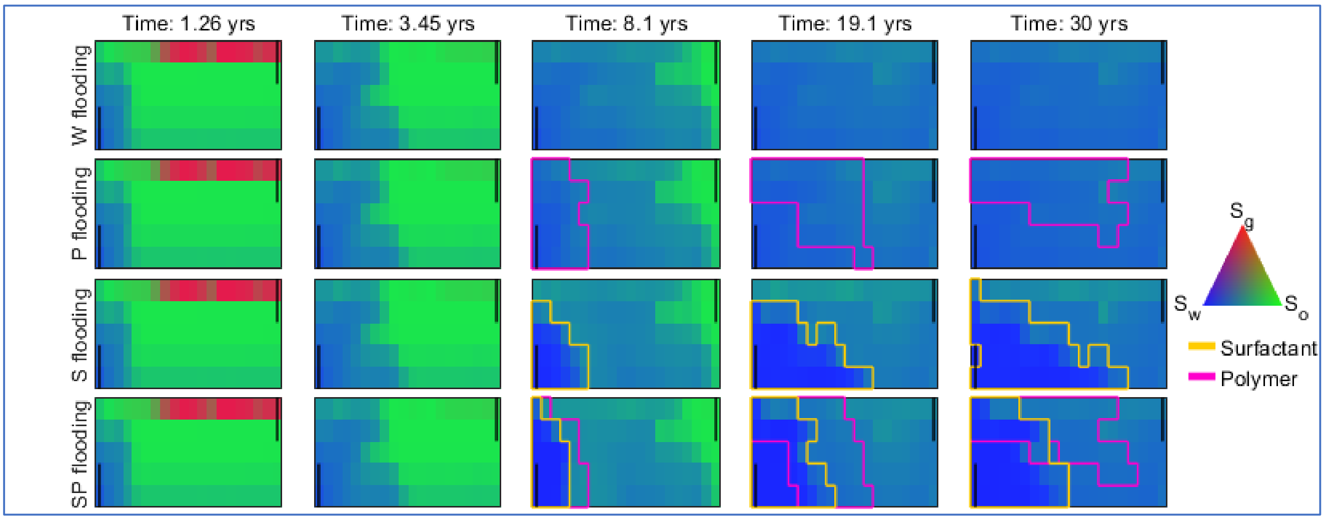


Figure 6. Progress in years of the front of our 4 agents. . **(**D.Zeqiraj**)**

Conclusions

In this paper, to our best knowledge, we tried for the first time to build a stochastic mixed integer nonlinear programming mathematical model for ranking and scheduling of EOR processes. This model, which in the full conviction of the author is not perfect is able to determine with acceptable proximity the hierarchy of EOR processes, the duration of these processes and the possibility of choosing the transition from one process to another. For solving the optimization problem, variants were used among which the package in Python called Pyomo. The Genetic Algorithm could have been used as in many similar cases with such problems, but the author of this paper preferred the ready-made package to leave no cause for possible errors. This paper was accompanied by examples with real data to better concretize the methodology used. The promising results of this paper are encouraging and serve as springboard for other challenges that appear on the horizon.

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