

## **Optimization of Polymer Flooding and Comparison with Infill Well Drilling**

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**Abstract:** *In a previous publication we introduced a methodology to assist in choosing between polymer flooding and infill well drilling.*

*Fractional flow analysis of any reservoir system for the two cases and the results obtained by applying Welge's graphical technique, at breakthrough, were introduced in previous paper to identify whether it is suitable for any particular recovery process, before a decision is made to undertake detailed reservoir simulation studies.*

*The objective of this paper is to conduct an economic analysis to investigate the impact of delaying the start of polymer flooding to identify whether it is better to start polymer flooding earlier or later in the life of the project, and to compare the polymer flooding scenario with a different scenario where infill well drilling is introduced. This is undertaken to illustrate the implementation of combined reservoir simulation and economic modelling.*

*It is achieved by performing a range of sensitivity calculations (reservoir simulation AND economic modeling), using Monte Carlo simulation (MCO) to establish confidence in the method and test uncertainties on key operational parameters input variables. These variables include oil, water and polymer production and injection costs, polymer concentration, timing, etc., and various economic factors such as; oil price, capital expenditure (CAPEX), polymer cost, etc. Sensitivity analysis graphs are developed to assess future engineering planning with regard to the economics of EOR projects. The analysis of uncertainty involves measuring the degree to which input contributes to uncertainty in the output.*

*These sensitivity calculations are numerous, and have been performed by developing a computer program, coded in Java. A total of 1,093,500 economic calculations were performed, based on 225 reservoir simulation calculations.*

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### **1. INTRODUCTION**

In the North Sea average recoveries are reported to be above 40% of initial oil in place. The Norwegian Petroleum Directorate in 2001 set a target of 50% recovery for the Norwegian sector of the North Sea and it was envisioned that EOR techniques could be used to achieve this target. However, many oil companies rely primarily on infill well drilling to increase recovery factors as their default option because with the information that they have they can target new wells to recover bypassed oil. EOR techniques involve a greater degree of uncertainty in predicating recovery factors, and therefore, risk and economic assessments are more difficult to perform Awan et al. (2008).

Infill drilling will permit production of oil from parts of the reservoir that might be bypassed by standard low density well spacing. Well spacing is the key to solving recovery problems caused by heterogeneity. In fields that have wells of varying ages, the production characteristics of older wells should be compared with those of new wells. It is not uncommon to find wells spaced in such a way that they are in very poor communication. This results from the fact that all reservoirs are heterogeneous to some degree or other El-Feky (1987).

Infill well drilling does not impact microscopic sweep efficiency but seeks to improve the macroscopic sweep efficiency by targeting oil that has not been swept by water. Due to gravity effects this bypassed oil is often to be found near the top of the reservoir and referred to as attic oil.

Polymer flooding is an EOR technology that can recover more oil by the inclusion of an additional oil displacement agent (the polymer), while injecting water to maintain the reservoir pressure. By

increasing the viscosity of the injected water, the polymer reduces the oil-water viscosity ratio, increases the sweep volume, and thus enhances oil recovery. Since 1975, the worldwide application of polymer flooding technology shows that the application of this technique can lead to an increase in recovery in the range 6% to 52% of OOIP. In China, polymer flooding has increased oil recovery by 10% based on the statistics from nearly 30 oilfields during the last 20 years. In 1997, China's production gain using polymer flooding reached  $3.03 \times 10^6$  t, and the number is  $15 \times 10^6$  t for the period 1996-2000 Zhang et al. (2010).

Addition of polymer to injection water increases the viscosity of the water and hence reduces the mobility of the displacing fluid, increasing the microscopic sweep efficiency. Macroscopic sweep efficiency is also improved by the reduction in channelling in heterogeneous reservoirs. Initially the polymer slug is displaced primarily into the high permeability zones so the mobility in these high permeability zones is reduced disproportionately. Subsequently injected fluid will increasingly displace hydrocarbons from the low permeability zones, improving overall sweep efficiency.

Wences et al. (2005) illustrated a process that enables the reservoir engineer to identify the optimum number of infill wells and locations, and to identify the appropriate EOR technique. The inputs include maximum flow rate, production and injection facilities, CAPEX and OPEX. The author also introduced a decision making process for both technical and economic risk analysis using Monte Carlo Simulation to generate a probabilistic model (P10, P50 and P90) of economic outputs such as NPV and Internal Rate of Return (IRR). In this paper also several sensitivities scenarios were made by modifying only one variable at time.

In this paper work, the combination between the operational parameters and the economic parameters will be numerous and a computer program will have to be developed to handle all the data. MCS will be performed to test the economic uncertainties and risk assessment associated with infill drilling and polymer flooding.

## 2. METHODOLOGY

The understanding of how the economic comparison should be performed is developed, since the timescales for investment and return on investment and the associated risks and uncertainties are different for polymer flooding projects and infill well drilling. The method involves studying a range of scenarios and modelling the impact these techniques have on recovery, and then running calculations of the impact of various options. An economic assessment is made of the costs and risks of the various options together with expected return under a range of economic scenarios. Initially a synthetic reservoir simulation model was developed to study the impact of polymer flooding vs. waterflooding. NPV was calculated for the economic comparison between the polymer flood and infill well scenarios. (The model was designed for polymer flood calculations, but can be easily adapted to assess other EOR methods.) The cash flow for this study was determined by generating the revenues by combining the oil production profile with the oil price profile. The revenues and cost are combined to yield a net cash flow. The cash flow is then discounted to obtain the cumulative discounted cash flow, or net present value of the project.

The equations are represented, respectively, by the following:

$$\text{Cash Flow (CF)} = \text{Revenue} - \text{Capital expenditure (CAPEX)} - \text{Operating expenditure (OPEX)} \quad (1)$$

### System Description

The simulation model (Figure 1)

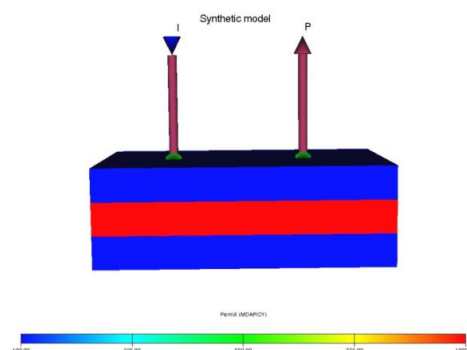


Figure 1. Synthetic model

- Dimensions
  - X 2250 feet
  - Y 1575 feet
  - Z 150 feet
- $K1 = 100\text{mD}$ ,  $K2 = 1000\text{mD}$ ,  $K3 = 100\text{ mD}$ ,  $Kv/Kh = 0.1$
- Porosities of 0.2, 0.22, and 0.2.
- Initial reservoir pressure: 4000 psi
- Injection rate: 2000 bbl/day
- Production BHP: 3500 psi
- Concentration of polymer: 1000 ppm (variable)
- The oil viscosity is 1.74 cP and the water viscosity is 0.8 cP.
- It is assumed that the injected water and the formation water are similar in composition.
- Period of injection:
  - Period of waterflooding (variable)
  - Period of polymer flooding (variable)
  - Period of waterflooding until reach 90% water cut
  - The distance between the injector well and the producer well is 1050 ft (320 m).
- A new production well was added to the water flooding model in 2011 to compare the recovery factor between infill well drilling and polymer flooding in terms of production (Figure 2).
- The production well was shut when the water cut reaches 90 %. The injecting well was controlled at an injection rate of 2000 bbl/day. The distance between the injector well and the producer well is 1050 ft (320 m) in the polymer flooding model. A new infill well was added to the model to compare the recovery factor between infill well drilling and polymer flooding in terms of production and economic feasibility. The distance between the oil production well (p) and the new infill well (i) is 450 ft (137 m).
- Total oil production was actually lower for the infill well simulations because in this case it was the water production rate that was accelerated and the water cut exceeded the 90% limit sooner – it was simply not a suitable scenario for infill well drilling.

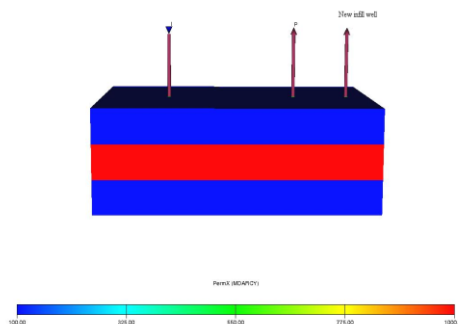


Figure 2. Synthetic model, with new infill well

### Sensitivity and Risk Analysis Including All Values of Economic Parameters

#### Reservoir simulation (simple two well synthetic model) for polymer flood

The procedure for the reservoir simulation calculations is as follows:

- 225 sensitivities have been run with polymer concentrations: 100, 200, 500, 1000, 1500 ppm.
- Three contiguous stages (total time up to 24 years):
  - Stage 1: Water flood
  - Stage 2: Polymer flood
  - Stage 3: Water flood for up to 12 years, depending on WCT
- Stage 1 commences in Year 1, and lasts between 3 and 11 years.
- Stage 2 lasts between 1 and 9 years.
- The following output is generated
  - Field oil production total (FOPT)
  - Field water production total (FWPT)
  - Field water injection total (FWIT)
  - Field polymer injection total (WCIT)
  - Field polymer production total (WCPT)

### **Reservoir simulation (simple three well synthetic model) for infill well drilling**

The result of the infill well drilling option in the simple synthetic model showed no significant increase in oil recovery for all timing of drilling the new wells. Thus infill well drilling would never be a viable option in this specific scenario, and so no further economic evaluation was carried out for infill well drilling. However, the purpose of these calculations is to establish the methodology, and so in future we will present results that include scenarios where infill well drilling is economically viable.

### **Economic model**

The procedure for the economic model is as follows:

- Input
  - Results of reservoir simulation calculations (identified above)
  - Economic parameters: infill well drilling cost, incremental well operating expenses, additional capital expenditure, polymer concentration, oil price, incremental oil production cost (IOPC), water injection cost (WIC), water production cost (WPC), polymer cost (PC), incremental polymer production cost (IPPC), incremental polymer injection cost (IPIC)
- Output
  - Incremental cash flow (ICF)
  - Derived performance measures
    - Net present value (NPV)

There are significant risks and uncertainties in the oil and gas industry that are associated with production. For the purpose of this study, quantifying uncertainty with ranges of possible values and associated probabilities helps everyone understand the risk involved. In this regard, we have been through some of the previous work performed by others who have had studied polymer injection to investigate a wide range of operational and economic parameters that affect polymer flooding.

Figure 3 shows the various permutations of periods of water flooding followed by polymer flooding that maintain a combined total of 12 years or fewer, leading to the 45 sensitivities that were run for each of the five polymer concentrations. Note that although in each case we assume a maximum of 12 years of waterflooding plus polymer flooding, we vary how many years of each in the sensitivity study in annual increments.

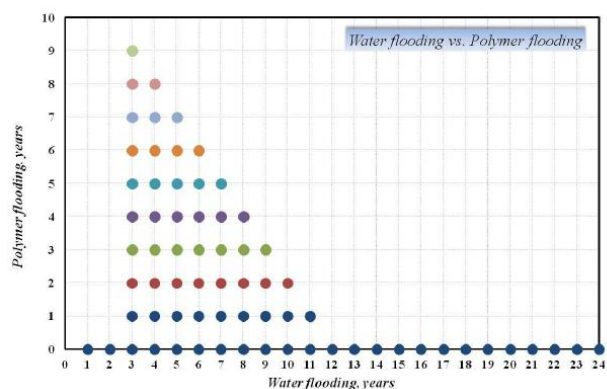


Figure 3. Number of years of polymer flooding and ensuing number of years of waterflooding

The variables that are used in this chapter to optimize the design, using project profitability measures as the decision making in the economic model are given in Table 1, and were obtained from the literature, Lefebvre et al. (2012), Alsofi et al. (2011); Buchgraber et al. (2009); Wang et al. (2007); Gharbi (2005); Wang et al. (2003). While the literature in some places gives ranges of values, which have been used here, for other parameters single values only are given. The objective of this analysis was to use ranges of parameters. However, certain parameters, such as the cost of specific types of polymer, can represent highly sensitive commercial information. As a result, building on the values given in the literature, ranges were proposed. The operator supporting this project was prepared to review the ranges proposed, and indicate that they were appropriate ranges for conditions such as those that prevail in the offshore North Sea oil industry, but without specifying where in that range the options they were considering lie. This was deemed the most suitable method to address the issue of obtaining information which is not available in the public domain, but which was required as input to this research activity, and without breaking any commercial confidentiality.

Table 1. Ranges used for economic parameters.

EOR technique	Water flooding	Polymer flooding	Infill well drilling
Duration of water flooding, year	3 to 11	3 to 11	3 to 11
Duration of polymer flooding, year	-	1 to 9	1 to 9
New infill wells	-	-	1
Infill well drilling cost, mm\$/well	-	-	5-10-15-20-25
Incremental Well Operating Expenses, mm\$/yr	-	-	0.5-1-1.5-2-2.5
Additional capital expenditure, mm\$	-	0.23-0.30-0.52-0.88-1.24	0
Polymer concentration, ppm	-	100-200-500-1000-1500	-
Oil Price, \$/bbl	30-50-80-115-150	30-50-80-115-150	30-50-80-115-150
Incremental oil production cost, \$/bbl	-	8-10-12	8-10-12
Water injection cost, \$/bbl	1-2-8	1-2-8	1-2-8
Water production cost, \$/bbl	1-2-3	1-2-3	1-2-3
Polymer cost, \$/lb	-	1-2-3-4	-
Incremental polymer production cost, \$/bbl	-	0-0.5-1	-
Incremental polymer injection cost, \$/bbl	-	0.25-0.5-1	-

### 3. RESULTS AND DISCUSSION

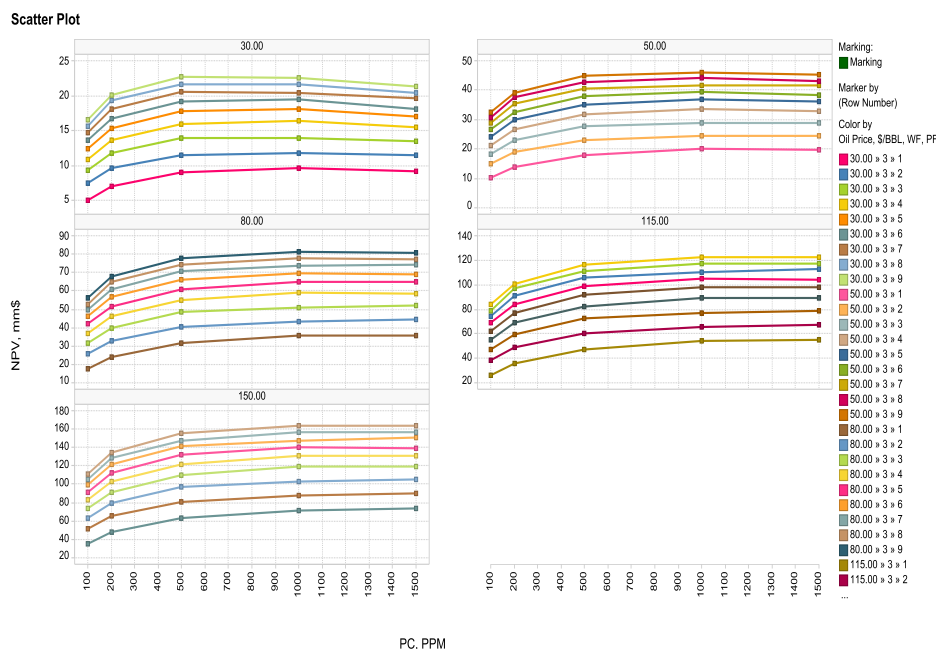
Production data output calculated from simulations of different concentrations of polymer injection and from infill well drilling, were imported into an economic model to evaluate the profitability using the following (base case) economic parameters: oil prices in range \$30-\$50/bbl, capital expenditure (CAPEX) is \$1 million, discount rate (DR) is 10%, incremental oil production cost is \$8/bbl, water injection cost is \$2/bbl, water injection cost is \$2/bbl, water production cost is \$2/bbl, polymer cost is \$1.50/lb, polymer injection cost is \$0.50/bbl and polymer production cost is \$0.50/bbl.

**Error! Reference source not found.** shows the relation between net present value and polymer concentration at different oil prices with economic parameters set as follows: water flooding 3 years; IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$1/lb; IPPC \$0/bbl; IPIC \$0.25/bbl.

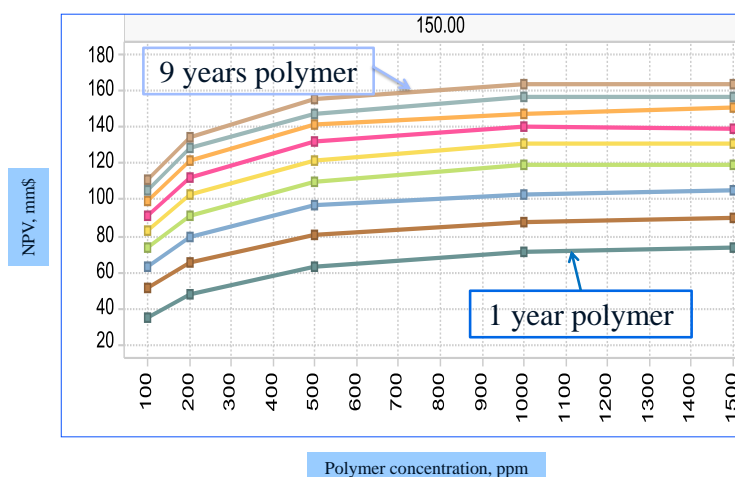
The results suggest that once infrastructure is in place, longer periods of polymer injection are better. However, there is little benefit to injecting polymer at concentration greater than 500 ppm Figure 5,

especially if there is a risk of low oil prices. The clarifications from the graphs are as follows:

- At low oil price, as concentration increases NPV rises then falls
- At high oil price, as concentration increases NPV rises continually, although the rate of increase is lower at high concentrations
- The later the start in polymer flooding, the lower the NPV
- The more years of polymer flooding, the higher the NPV (the lowest curve on each graph is for 1 year of polymer flooding, the highest curve is for 9 years, with the lines in between increasing by one year at a time)



Error! Reference source not found.. Net present value vs. polymer concentrations at different oil prices when the polymer is injected after 3 years of waterflooding; each graph is for a different oil price (\$30, \$50, \$80, \$115, \$150/bbl). On the x-axis is polymer concentration, on the y-axis is NPV. Each line is for a different number of years of polymer flooding (1-9).



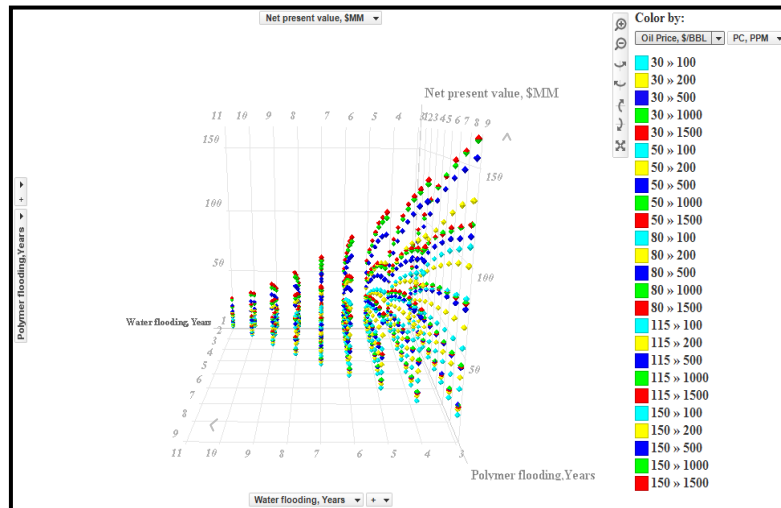
Error! Reference source not found.. Net present value vs. polymer concentrations at \$150 oil prices when the polymer is injected after 3 years of waterflooding. Each line is for a different number of years of polymer flooding (1-9).

**Error! Reference source not found.** shows the 3D Scatter plot of NPV (on the z axis) as a function of the number of years of polymer flooding (on the x axis) and as a function of the number of years of water flooding before the EOR project (on the y axis), for all polymer concentrations (100, 200, 500, 1000, and 1500 ppm), and all oil prices (\$30, \$50, \$80, \$115, and \$150/bbl) with economic parameters set as follows: IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$1/lb; IPPC \$0/bbl; IPIC

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\$0.25/bbl. The data shown here is plotted with the Spotfire (TM) software. The observations made include:

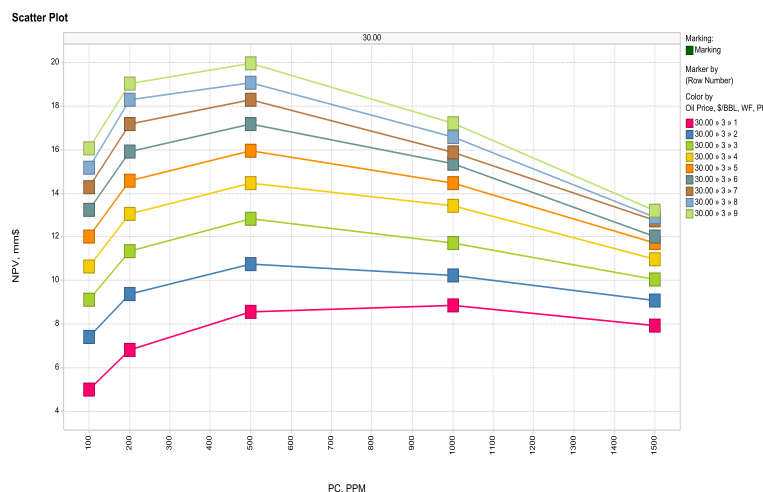
- Highest NPV occurs where we have the shortest period of water flooding and longest period of polymer flooding; this is true for all polymer concentrations and all oil prices.
- At this relatively low polymer cost (PC = \$1/lb) the highest NPV is achieved with the highest polymer concentrations
- The later the start in polymer flooding, the lower the NPV



Error! Reference source not found. 3D Scatter plot of NPV vs number of years of polymer flooding (PF), and number of years of water flooding (WF) for polymer concentrations in range 100, 200, 500, 1000, and 1500 ppm, and oil prices in range \$30, \$50, \$80, \$115, and \$150/bbl

Error! Reference source not found. shows the relation between net present value and polymer concentration at oil price of \$30/bbl with economic parameters set as follows: WF 3 years; IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$4/lb; IPPC \$0/bbl; IPIC \$0.25/bbl. The observations we make from this graph are as follows:

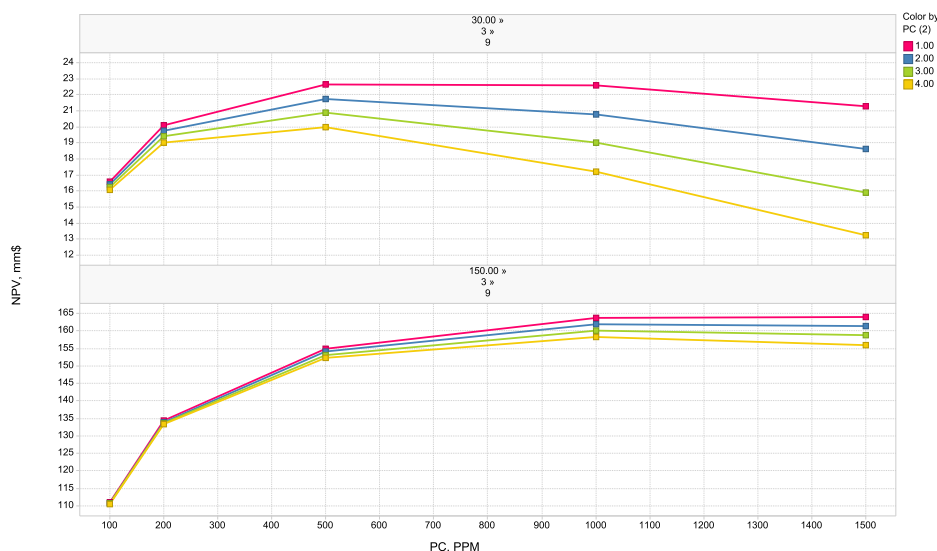
- With a polymer cost increase to \$4/lb, the optimum polymer concentration reduces to 500 ppm.
- NPV increased with increased polymer concentration from 100 to 500 ppm at the increased polymer cost when the oil price is \$30/bbl.
- NPV decreased with increased polymer concentration from 500 to 1500 ppm at the increased polymer cost when the oil price is \$30/bbl.



Error! Reference source not found. Net present value vs. polymer concentrations with polymer cost \$4/lb and \$30/bbl oil price when the polymer is injected for between 1 and 9 years after 3 years of waterflooding

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concentration at oil price of \$30/bbl with economic parameters set as follows: WF 3 years; PF 9 years; IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$1-\$4/lb; IPPC \$0/bbl; IPIC \$0.25/bbl).



Error! Reference source not found. *Net present value vs. polymer concentrations with polymer cost (1-4 \$/lb) and \$30/bbl oil price when the polymer injected for 9 years after 3 years of waterflooding*

Here, we conclude that:

- More significantly, at \$30/bbl oil price the NPV decreases with increasing polymer concentration for concentration above 500 ppm, especially at higher polymer costs, whereas at \$150/bbl, the NPV continues to increase as polymer concentration is increased.
- NPV decreased with increased polymer cost (PC) at both an oil price of \$30/bbl and also at \$150/bbl. However, at \$30/bbl the relative impact of the polymer cost is more evident.

Error! Reference source not found. shows the probability distribution of net present values at oil price of \$30 and different polymer concentrations of 100, 200, 500, 1000, and 1500 ppm with economic parameters set as follows: WF 3 years; IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$4/lb; IPPC \$0/bbl; IPIC \$0.25/bbl. We note that the standard deviation initially increases with polymer concentration, with slight attenuation from 1000 to 1500ppm.

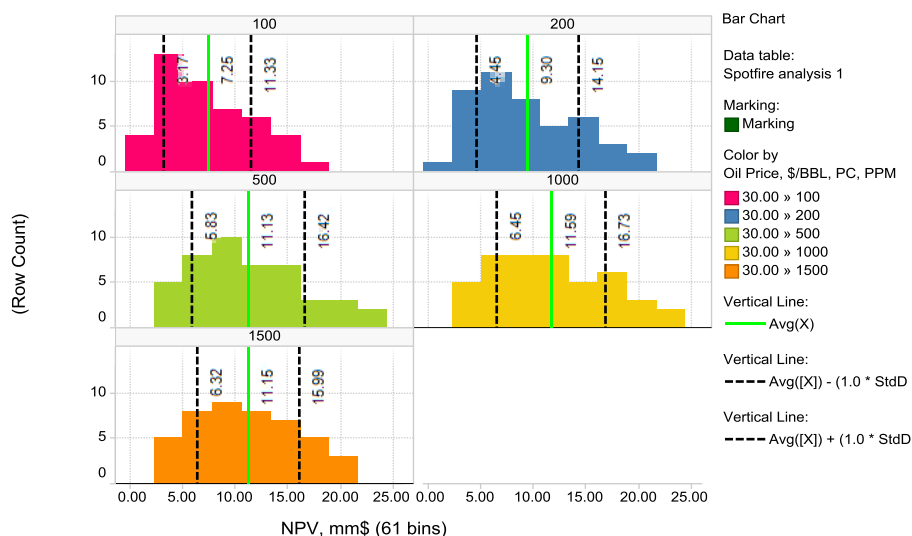


Figure 9. Probability distribution of net present value at different polymer concentration of 100, 200, 500, 1000, and 1500 ppm and \$30/bbl oil price

Error! Reference source not found. shows the probability distribution of net present values at oil price of \$150/bbl and the different polymer concentrations of 100, 200, 500, 1000, and 1500 ppm with economic parameters set as follows: WF 3 years; IOPC \$8/bbl; WIC \$1/bbl; WPC \$1/bbl; PC \$4/lb; IPPC \$0/bbl; IPIC \$0.25/bbl. Again, we note that the standard deviation initially increases with polymer concentration, with slight attenuation from 1000 to 1500ppm.



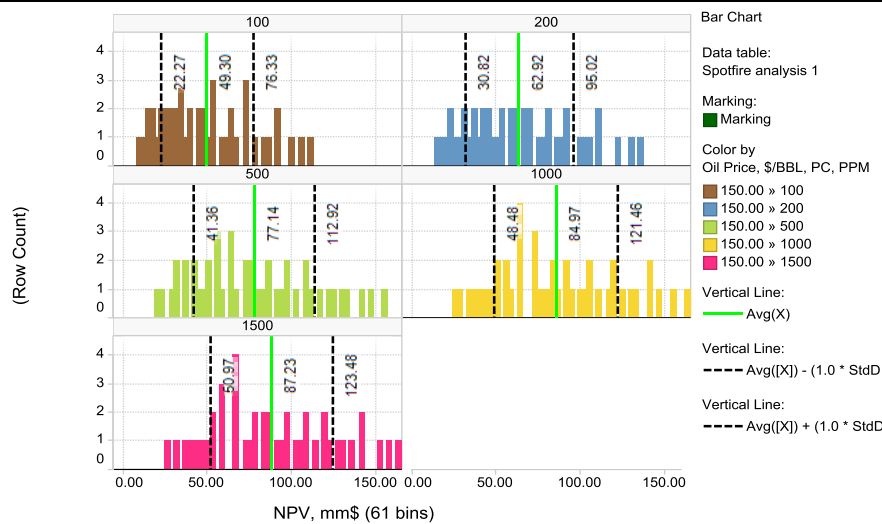


Figure 10. Probability distribution of net present value at different polymer concentration of 100, 200, 500, 1000, and 1500 ppm and \$150/bbl oil price

An example of the type of output obtained from the economic model is shown in Table 2.

Table 1 Part of table of 1,093,500 lines of data containing full range of economic calculations specified in Table 2.

PC	WF	PF	Oil Price	IOPC	WIC	WPC	PC (2)	IPPC	IPIC	NPV	NPVI	MCO
100	3	1	30.00	8.00	1.00	1.00	1.00	0.00	0.25	5.07	22.05	0.23
100	3	1	30.00	8.00	1.00	1.00	1.00	0.00	0.50	4.91	14.67	0.33
100	3	1	30.00	8.00	1.00	1.00	1.00	0.00	1.00	4.57	6.85	0.67
100	3	1	30.00	8.00	1.00	1.00	1.00	0.50	0.25	3.51	15.25	0.23
100	3	1	30.00	8.00	1.00	1.00	1.00	0.50	0.50	3.34	9.99	0.33
100	3	1	30.00	8.00	1.00	1.00	1.00	0.50	1.00	3.01	4.51	0.67
100	3	1	30.00	8.00	1.00	1.00	1.00	1.00	0.25	1.94	8.45	0.23
100	3	1	30.00	8.00	1.00	1.00	1.00	1.00	0.50	1.78	5.31	0.33
100	3	1	30.00	8.00	1.00	1.00	1.00	1.00	1.00	1.44	2.16	0.67
100	3	1	30.00	8.00	1.00	1.00	2.00	0.00	0.25	5.04	21.93	0.23
100	3	1	30.00	8.00	1.00	1.00	2.00	0.00	0.50	4.88	13.45	0.36
100	3	1	30.00	8.00	1.00	1.00	2.00	0.00	1.00	4.55	6.54	0.70
100	3	1	30.00	8.00	1.00	1.00	2.00	0.50	0.25	3.48	15.13	0.23
100	3	1	30.00	8.00	1.00	1.00	2.00	0.50	0.50	3.31	9.13	0.36
100	3	1	30.00	8.00	1.00	1.00	2.00	0.50	1.00	2.98	4.29	0.70
100	3	1	30.00	8.00	1.00	1.00	2.00	1.00	0.25	1.91	8.33	0.23
100	3	1	30.00	8.00	1.00	1.00	2.00	1.00	0.50	1.75	4.82	0.36
100	3	1	30.00	8.00	1.00	1.00	2.00	1.00	1.00	1.42	2.04	0.70
100	3	1	30.00	8.00	1.00	1.00	3.00	0.00	0.25	5.02	21.81	0.23
100	3	1	30.00	8.00	1.00	1.00	3.00	0.00	0.50	4.85	12.41	0.39
100	3	1	30.00	8.00	1.00	1.00	3.00	0.00	1.00	4.52	6.24	0.72
100	3	1	30.00	8.00	1.00	1.00	3.00	0.50	0.25	3.45	15.01	0.23
100	3	1	30.00	8.00	1.00	1.00	3.00	0.50	0.50	3.29	8.40	0.39
100	3	1	30.00	8.00	1.00	1.00	3.00	0.50	1.00	2.95	4.08	0.72
100	3	1	30.00	8.00	1.00	1.00	3.00	1.00	0.25	1.89	8.20	0.23
100	3	1	30.00	8.00	1.00	1.00	3.00	1.00	0.50	1.72	4.40	0.39
100	3	1	30.00	8.00	1.00	1.00	3.00	1.00	1.00	1.39	1.92	0.72
100	3	1	30.00	8.00	1.00	1.00	4.00	0.00	0.25	4.99	19.74	0.25
100	3	1	30.00	8.00	1.00	1.00	4.00	0.00	0.50	4.82	11.50	0.42
100	3	1	30.00	8.00	1.00	1.00	4.00	0.00	1.00	4.49	5.97	0.75
100	3	1	30.00	8.00	1.00	1.00	4.00	0.50	0.25	3.42	13.55	0.25
100	3	1	30.00	8.00	1.00	1.00	4.00	0.50	0.50	3.26	7.77	0.42
100	3	1	30.00	8.00	1.00	1.00	4.00	0.50	1.00	2.92	3.89	0.75

#### 4. CONCLUSIONS

In this paper the methodology has been developed using a synthetic model by conducting an economic analysis and the results suggest that once infrastructure is in place, longer periods of polymer injection are better. However, there is little benefit to injecting polymer at concentration greater than 500 ppm, especially if there is a risk of low oil prices. The earlier the start in injecting polymer in the life of the project, the better it is with regard to oil recovery comparing and NPV.

The result of the infill well drilling option in the simple synthetic model showed no significant increase in oil recovery for all timing of drilling the new wells. Thus infill well drilling would never be a viable option in this specific scenario, and so no further economic evaluation was carried out for infill well drilling. This highlights that sometimes the outcome will become obvious for technical reasons, and thus the full economic analysis will not be required.

The results presented here apply to this system only. In the next paper we will consider other systems,

and although applying the same methodology, may arrive at quite different conclusions.

Based on the economic calculations output using the Spotfire software for this simple synthetic system we have identified that:

1. With economic parameters set as follows: WF3years; PF 9 years; IOPC\$8/bbl; WIC\$1/bbl; WPC\$1/bbl; PC\$1/lb; IPPC\$0/bbl; IPIC\$0.25/bbl for all polymer concentrations (100, 200, 500, 1000, and 1500 ppm), and all oil prices (\$30, \$50, \$80, \$115, and \$150/bbl):
  - a) At low oil price, as polymer concentration increases NPV rises then falls, with an optimum NPV at 500 ppm
  - b) At high oil price, as concentration increases NPV rises continuously
2. With economic parameters set as follows: IOPC\$8/bbl; WIC\$1/bbl; WPC\$1/bbl; PC\$1/lb; IPPC\$0/bbl; IPIC\$0.25/bbl) for all polymer concentrations (100, 200, 500, 1000, and 1500 ppm), and all oil prices (\$30, \$50, \$80, \$115, and \$150/bbl):
  - a) Highest NPV occurs where we have shortage period of water flooding and longest period of polymer flooding; this is true for all polymer concentrations and at all oil prices.
  - b) At this relatively low polymer cost (PC = \$1/lb) the highest NPV is achieved with the highest polymer concentrations
3. With economic parameters set as follows: WF3 years; PF 1 to 9 years; IOPC\$8/bbl; WIC\$1/bbl; WPC\$1/bbl; PC\$4/lb; IPPC\$0/bbl; IPIC\$0.25/bbl) all polymer concentrations (100, 200, 500, 1000, and 1500 ppm), and \$30/bbl oil price:
  - a) As polymer cost increases, the optimum polymer concentration reduces to 500 ppm.
  - b) NPV increased with increased polymer concentration from 100 to 500 ppm at increased polymer cost with an oil price of \$30/bbl.
  - c) NPV decreased with increased polymer concentration from 500 to 1500 at increased polymer cost when the oil price is \$30/bbl.
4. With economic parameters set as follows: WF3 years; PF9 years; IOPC\$8/bbl; WIC\$1/bbl; WPC\$1/bbl; PC\$1-\$4/lb; IPPC\$0/bbl; IPIC\$0.25/bbl):
  - a) At \$30/bbl oil price the NPV decreases with increasing polymer concentration for concentrations above 500 ppm, especially at higher polymer costs, whereas at \$150/bbl, the NPV continues to increase as polymer concentration is increased.
  - b) NPV decreased with increased polymer cost (PC) at both an oil prices \$30/bbl and also \$150/bbl. However, at \$30/bbl the relative impact of the polymer cost is more evident.
  - c) Standard deviation initially increases with polymer concentrations (100, 200 and 500 ppm), with slight attenuation from 1000 to 1500ppm.

In summary, at lower oil prices, the NPV is more sensitive to polymer cost, and for the higher polymer costs, the optimum concentration tends to decrease, with an optimum concentration of 500 ppm being observed for polymer costs of \$4/lb. At higher oil prices, the system is less sensitive to polymer cost, and higher polymer concentrations may be beneficial, up to 1000 ppm. In all cases, the earlier that polymer injection is started then the higher the resulting NPV.

### **Recommendations and future work**

Based on the initial output for this simple synthetic system we have identified that:

- Further analysis of types of output using Spotfire would be beneficial. This software is evidently a very powerful tool for displaying data where there are multiple dependencies, as here, where there are numerous economic and reservoir engineering inputs to consider, which have led to over 1 million realisations. This analysis would not have been possible with conventional plotting software.
- Application should next be made to a field where the choice has already been made (infill well drilling), to test the robustness of the method against a conventional decision making process for which there is historical data.
- Following this, application should be carried out in a field where the choice has yet to be made, for example in a field which has been undergoing waterflood, and where the operator is considering polymer flooding as an alternative (or in addition) to infill well drilling.

**Nomenclature**

<i>BHP</i>	<i>Bottom hole pressure</i>	<i>PSI</i>
<i>CAPEX</i>	<i>Capital expenditure</i>	<i>\$ Million</i>
<i>EOR</i>	<i>Enhanced Oil Recovery</i>	
<i>DR</i>	<i>Discount rate</i>	<i>%</i>
<i>FOPT</i>	<i>Field oil production total</i>	<i>bbl</i>
<i>FWPT</i>	<i>Field water production total</i>	<i>bbl</i>
<i>FWIT</i>	<i>Field water injection total</i>	<i>bbl</i>
<i>i</i>	<i>Discount rate</i>	<i>%</i>
<i>ICF</i>	<i>Incremental cash flow</i>	<i>\$ Million</i>
<i>IPIC</i>	<i>Incremental polymer injection cost</i>	<i>\$/bbl</i>
<i>IOPC</i>	<i>Incremental oil production cost</i>	<i>\$/bbl</i>
<i>IPPC</i>	<i>Incremental polymer production cost</i>	<i>\$/bbl</i>
<i>NPV</i>	<i>Net present value</i>	<i>\$ Million</i>
<i>OPEX</i>	<i>Operating expenditure</i>	<i>\$ Million</i>
<i>PC</i>	<i>Polymer concentration</i>	<i>ppm</i>
<i>PC (2)</i>	<i>Polymer cost</i>	<i>\$/lb</i>
<i>PF</i>	<i>Polymer flooding</i>	
<i>WF</i>	<i>Water flooding</i>	
<i>WIC</i>	<i>Water injection cost</i>	<i>\$/bbl</i>
<i>WCIT</i>	<i>Field polymer injection total</i>	<i>mmlb</i>
<i>WCPT</i>	<i>Field polymer production total</i>	<i>mm lb</i>
<i>WCT</i>	<i>Water cut</i>	<i>%</i>
<i>WPC</i>	<i>Water production cost</i>	<i>\$/bbl</i>

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