SPE 155657

Comparison between Conventional and Intelligent Wells with Reactive and Proactive Controls under Economic Uncertainty

M. A. Sampaio, C. E. A. G. Barreto, and D. J. Schiozer, SPE, State University of Campinas

Copyright 2012, Society of Petroleum Engineers

This paper was prepared for presentation at the SPE International Production and Operations Conference and Exhibition held in Doha Qatar, 14–16 May 2012.

This paper was selected for presentation by an SPE program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of SPE copyright.

Abstract
The exploitation of an oil field in deep water presents many challenges related to high water production, high cost of frequent well interventions and many uncertainties. One of the technologies available, which can overcome these problems, is the use of intelligent wells (IW), which are capable of reducing water production rates, to avoid intervention in the well and to add operational flexibility to mitigate risk. However, the real benefits of this technology are not always clear due to the lack of a consolidated methodology in the literature. Moreover, there are also two main ways of controlling valves, i.e., reactive and proactive controls, making it necessary to better understand them to extract advantages and disadvantages from each one. Therefore, the objective of this work is the comparison between conventional wells (CW) and IW, using reactive and proactive controls. The first control is simpler to be used and quicker to be optimized but the second type can be more profitable, although more difficult to optimize. The optimization method used to solve the problem is an evolutionary algorithm, which is coupled to a commercial simulator to search for the maximum net present value (NPV), based on the 'shut in' water cut to determine the optimum time in which to close each valve and the well, in all types of controls. This work employs a model using an inverted five-spot configuration of wells to represent a part of a reservoir under a waterflooding recovery method. Some case studies are used considering different reservoir heterogeneities, type of oil and under economic uncertainty. The conclusion shows that IWs are able to increase production time, oil recovery and the NPV; as a consequence total water production is also increased. The results also show higher benefits in cases with more heterogeneity and light oil. Moreover, IWs using proactive control is better than IWs with reactive control and using either of them is better than CWs.

Introduction
One of the technologies available to avoid high water production and costly well intervention is the intelligent completion. Intelligent wells (IW) are capable of adding operational flexibility to respond to (or to prevent) undesired events in order to increase oil production. However, this technology is more expensive than that of a CW, making it necessary to estimate the benefits, which should offset the investment of this completion.

Unfortunately, the comparison between IWs and CWs is not easily done, since optimization of well controls may be time consuming and make the problem very complex. Several studies employed different methods to solve this problem: conjugate gradient (Kharghoria *et al.*, 2002; Yeten *et al.*, 2002), simulated annealing (Kharghoria, 2002), and a gradient-based method (Sarma *et al.*, 2005, Van Essen *et al.*, 2009, Yeten *et al.*, 2004), among others. Although some of these studies have shown benefits, there is not a quick and efficient optimization method to solve these problems when real reservoirs, with many wells, are considered. This study employs an evolutionary algorithm, because this algorithm shows better performance when searching for the global solution of problems, even increasing the number of required simulations.

The computational effort required to optimize IW operation is proportional to the kind of operation chosen to control the valves. Basically, there are two different operations for inflow control valves (ICV): proactive (defensive) and reactive controls. The first operates to prevent a future undesired event. Thus, ICVs work to prevent or to avoid excessive production of unwanted fluids through the best configuration of valve aperture during the field's production time. For the second control (reactive), the ICVs operate only when an "undesired" event occurs; the selected event can be, for instance, high water or gas production (Ebadi & Davies, 2006; Addiego-Guevara et al., 2008). In theory, proactive control should yield better results, because it is a type of control that operates before or at the very same time that an undesired event occurs. However, this type of control is more appropriate when there is a good knowledge of the reservoir and confidence in the prediction of production and economic scenario. Also, it is more difficult to optimize the ICV control because it is necessary to use one variable at least for each valve.

The reactive control can be used, for example, to determine where and how many valves can be installed in the well, decreasing the number of simulations without loss of quality of results. However, it is necessary to carry out more studies demonstrating its benefits and methods for making this decision. Moreover, the proactive control can be used to evaluate the potential production of a field, using the intelligent completion.

Thus, the aim of this work is the comparison between IW, with two types of control, reactive and proactive, and conventional wells in the exploitation of an oil field, under economic uncertainties.

Methodology

The methodology of this work consists of three steps:

1) Representation of Intelligent Wells and Valves in the Simulator

In the appropriate representation of ICV control in a commercial simulator, the layers of the well are grouping. The time of closing valves is determined by a monitoring parameter. The parameter chosen as the guide to choose the time to close the valve is a 'shut in' water cut (WCUT). Therefore, the optimization method consists of finding the optimum 'shut in' water cut. The valves operate in an open-close system (on/off), determined by the optimal time to close each valve found by an algorithm.

2) Optimization of ICV Operation

This paper employs an evolutionary algorithm, an optimization method that performs the search for an optimal solution using concepts of the theory of evolution (Baeck, Fogel and Michalewicz, 2000). This method is based on the simulation of the evolution of species through selection, reproduction and mutation. It uses a population of structures called individuals. In these structures, operators are applied, such as crossover and mutation, among others. Each individual is submitted to an evaluation that assigns its quality as a solution to the problem. This assessment will determine the survival of the best-adapted individuals that will participate in the reproduction of the next generations.

To solve the problem, a program was coupled to a commercial reservoir simulator. The individuals in this study are the values of the WCUT used to set the time to close each of the valves of the IW or the entire CW. Reopening of previously closed ICV is not allowed in this methodology. The objective function to be maximized in the program is the field's NPV. Thus, the methodology can find an optimal operation to close the well's valves at different times over the period of field exploitation.

Figure 1 shows the flowchart, which summarizes the steps taken to optimize the closing of the valves.

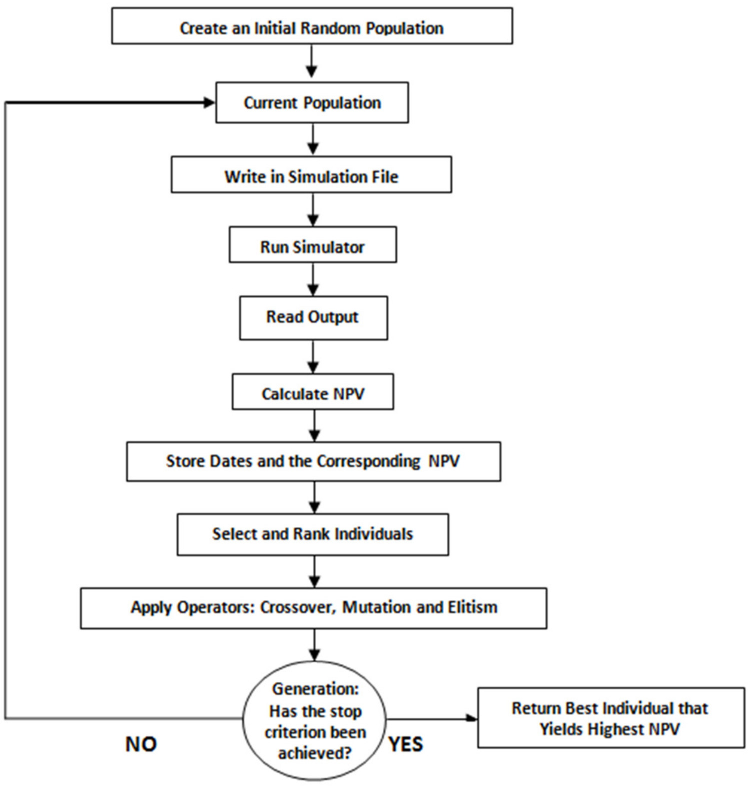


Figure 1: Flowchart of the optimization framework

For proactive control, the undesired event here is the negative cash flow in any of well's valves. In this case, the closing of some valves before others is allowed, but this only occurs if one of them starts with a negative cash flow and leads to an increase in the well's NPV.

Some premises are used in this optimization process:

- Well operational targets do not change during this procedure: maximum producer and injector flow rates; minimum BHP of the producers and maximum BHP of the injector. The parameter considered in the optimization process is the time at which to close each of the IW's valves.
- The objective function is the NPV; oil and water production and water injection are used to analyze the results.

3) Analysis of Economic Uncertainty

To evaluate the performance of an IW under economic uncertainty, the difference of expected monetary value (EMV) between an IW and a CW is used (ΔEMV), which takes into account the probability of the occurrence of each economic scenario, given by:

$$\Delta EMV = \sum_{i=1}^{3} p_i . \Delta NPV_i \quad (1)$$

where p_i is the probability of the occurrence and ΔNPV_i is the difference between NPV of an IW and a CW for each economic scenario.

Application

In this work, a synthetic reservoir model is selected, based on the properties of Brazilian reservoirs, representing a part of a reservoir studied with a maximum simulation time of 30 years and under a water injection recovery method.

To analyze the performance of two types of control valves of an IW and compare them with a CW, three cases are considered:

- Case 1: lower heterogeneity and light oil
- Case 2: higher heterogeneity and light oil
- Case 3: higher heterogeneity and heavy oil

These three cases are studied in three economic scenarios: pessimistic, optimistic and probable (whose details are given below). Each case is optimized for each of the economic scenarios, as seen in Figure 2 below.

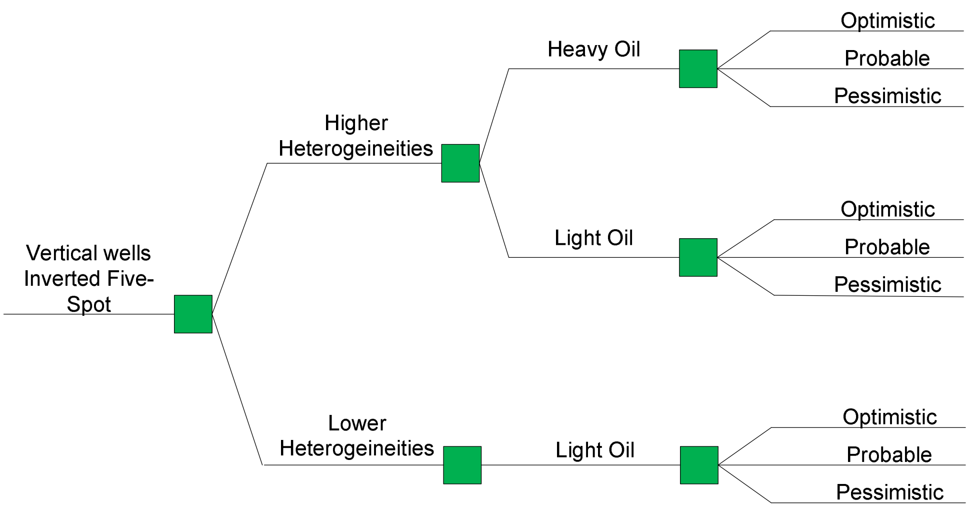


Figure 2: Scheme of each optimization performed

Reservoir Model

The examples tested here represent part of a given reservoir that represents a region between one injector and 4 producers. The dimensions are 20x20x10m and the grid dimension is 21x21x10 blocks. Table 1 presents the data of the model's rock and fluid properties.

Table 1: Properties of Rock and Fluids

Reference Pressure of Rock	315.56 (bars)
Compressibility of Rock	5.41×10^{-5} (bars^{-1})
Reference Pressure of Water	0.98 (bars)
Compressibility of Water	4.99×10^{-5} (bars^{-1})
Density of Water	1.01

The cases of light oil have a density of 31.9°API and the case of heavy oil has a density of 19.4°API. Table 2 presents the properties for the heterogeneity of the cases.

Table 2: Distribution of permeability and porosity

	Lower heterogeneity	*Higher heterogeneity*
Permeability in x	Lognormal (μ=200mD, σ=50mD)	Lognormal (μ=500mD, σ=200mD)
Permeability in y	Equal permeability in x	130% of permeability in x
Permeability in z	10 % of permeability in x	10 % of permeability in x
Porosity	Normal (μ=0.25, σ=0.05)	Normal (μ=0.25, σ=0.05)

Well Configurations

An inverted five-spot configuration with four vertical producers on the corners and a single injector at the center is used (Figure 3).

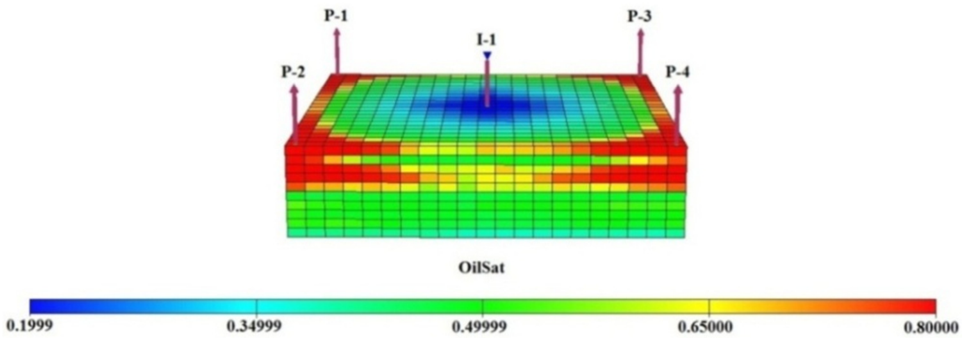


Figure 3: Reservoir model used in this work

The producers contain five ICVs, one for each two layers and a total of 20 valves. The operational restrictions of the wells are listed in Table 3.

Table 3: Operational restrictions of the wells

Producers		*Injector*	
Control Mode	Liquid Production	Control Mode	Water Rate
Maximum Rate	175 m^3/day	Maximum Rate	2400 m^3/day
Minimum BHP	200 bars	Maximum BHP	400 bars

For injectors, the maximum rate of water injection is equivalent to the fluid production volume, considering reservoir conditions to avoid high pressurization.

Evolutionary Algorithm Parameters

Table 4 presents the evolutionary algorithm parameters used in each type of control. For the CWs, it is necessary to maximize NPV, having as the only variable the WCUT for each well. The same occurs for the IWs with reactive control; only one optimum WCUT which is equal for all valves (one for each well). For the IWs with proactive control, five variables are used, corresponding to the optimal WCUT of each valve.

Table 4: Evolutionary algorithm parameters

	Conventional Wells	*Intelligent Wells: Reactive Control*	*Intelligent Wells: Proactive Control*
Number of Generations	40	40	180
Size of Population	20	20	60
Number of Elite Individuals	2	2	2
Crossover Rate	0.8	0.8	0.8

Economic Scenarios

To analyze the valve's operation using two controls for the IWs and the CWs under economic uncertainty, three economic scenarios are considered: pessimistic, probable and optimistic. The values for each scenario are shown in Table 5.

Table 5: Economic data

Economic Scenarios	*Discount Rate (% p.a.)*	*Oil Price (USD/bbl)*	*Oil Production Cost (USD/bbl)*	*Water Production Cost (USD/bbl)*	*Water Injection Cost (USD/bbl)*
Optimistic	8.8	65.00	8.00	0.70	1.00
Probable	8.8	50.00	8.00	1.00	1.00
Pessimistic	8.8	35.00	8.00	1.50	1.00

The economic base model is selected following a simplified Brazilian fiscal regime, assuming the data presented in Table 6.

Table 6: Economic parameters used in a simplified Brazilian fiscal regime

Economic parameter	*Value*
Corporate tax	25%
Royalties	10%
Social contribution	9%
Linear Depreciation (years)	10

In all cases, the presented value is reduced by the investment value of USD 70 million, corresponding to the sum of the investments in the platform, drilling of conventional wells and cost of abandonment. This relatively low value is proportional to the investment that would be made in a field with several wells, i.e., an estimated value considering this model as a sector of a field.

The values of Table 7 below are considered for the additional investment of intelligent completion with on/off type valves. With these values, the producer IWs with five on/off type valves has a cost of USD 625,000. It should be noted that the cost of intelligent completion is an estimation of an average cost, since the real cost of each valve depends on the material and its technical specifications. In the economic analysis of this work, the differences in NPV between the CWs and the IWs are considered for each case, determining the relative profitability of using this technology.

Table 7: Additional cost for intelligent completion

	Cost of Intelligent Completion (USD)
Intelligent completion on/off	200,000
Additional for each on/off zone	85,000

The probabilities used in this work are given in Table 8 below.

Table 8: Uncertainty of economic scenarios

	Pessimistic	*Probable*	*Optimistic*
Oil Price (USD/bbl)	35.00	50.00	65.00
Water Production Cost (USD/bbl)	1.50	1.00	0.70
Probability	25%	50%	25%

Results and Discussions

Here, Case 2 is presented with more details (a more heterogeneous model, with light oil), since it is the case in which the IW presents its best performance. The main results will be presented for the remaining cases.

Probable Economic Scenario of Case 2

Table 9 shows the results obtained for the optimization of a CW and an IW. It can be seen that the IWs are able to increase oil production and NPV when compared to the CW, while reducing water production with reactive control. The differences between the NPV of an IW and a CW (ΔNPV) are also presented to evaluate the profitability after investment in intelligent completion.

Table 9: Production of a CW and an IW for the probable scenario

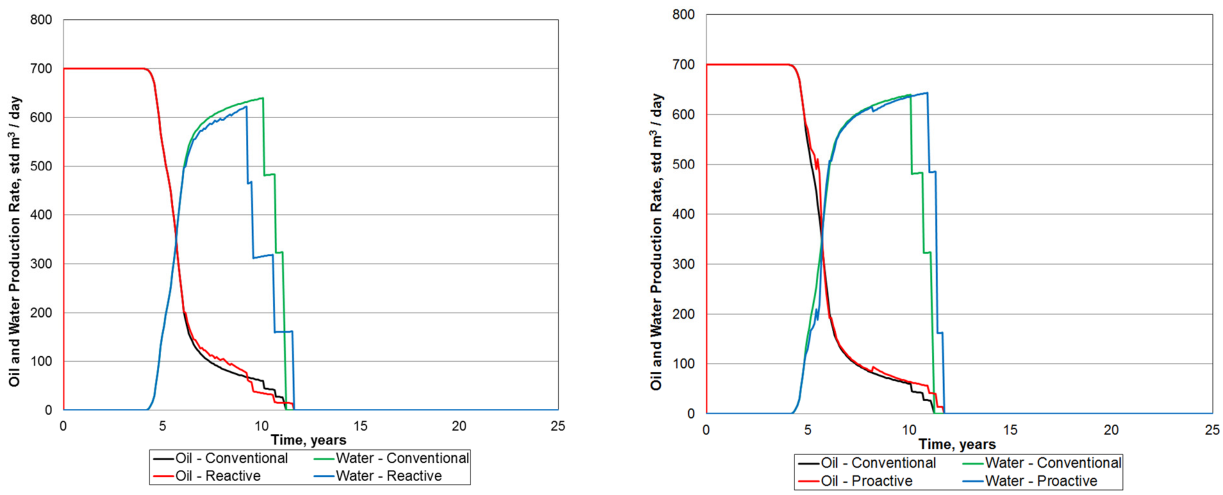
Probable Scenario	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.57	1.44	3.54	53.29	0
Intelligent - Reactive	1.59	1.42	3.54	53.75	0.46
Intelligent - Proactive	1.60	1.53	3.68	54.11	0.82

Table 10 shows the percentage of different types of completion for the two types of control; an IW in relation to a CW. The results show that proactive control is better than reactive control to maximize the NPV.

Table 10: Percentage Differences in indicators for an IW in relation to a CW for the probable scenario

Probable Scenario	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	+ 1.25 %	- 1.39 %	+ 0.20 %	+ 0.86 %
Intelligent - Proactive	+ 1.94 %	+ 6.32 %	+ 3.77 %	+ 1.52 %

Figure 4 shows the results of IWs production for all producers (sum of 4 producer wells) with the two controls acting jointly with the results of the CWs. The first graph shows that the IWs with reactive control can produce longer and with smaller water production rates over time in relation to CWs. The second graph also shows that the IWs with proactive control can produce longer than CWs, but, in this case, resulting in higher water production.



(a) **(b)**

Figure 4: Production of two types of control valves for intelligent and conventional wells (a) reactive; (b) proactive

Figure 5 highlights the time at which each valve closes in the IW and the time at which the CW closes for producer well P-1. It can be seen that the layers with higher permeability are those whose valves close first, since the water arrives earlier in these valves. It should be noted that the evolutionary algorithm did not find the optimal solution for proactive control, since it is a subcase of reactive control and the IW with two types of control closed at the same time. This indicates that the solution to proactive control is probably a suboptimal solution.

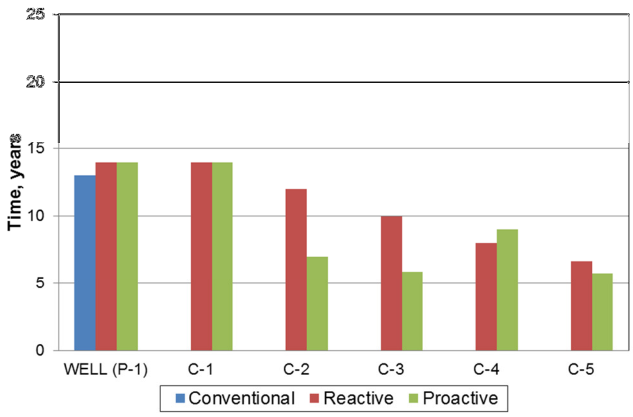
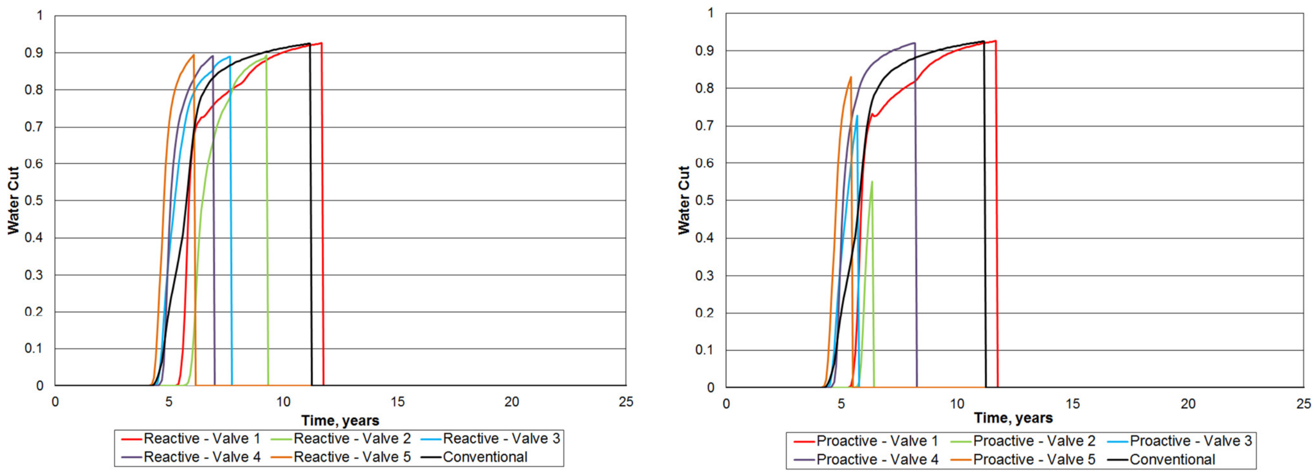


Figure 5: Closing valves for IW (completions C1 to C5) and CW (well) (P-1)

Figure 6 shows the increase in water cut in the well and in each region, i.e., the water cut in each valve for only producer well P-1. These figures show that the valves close in accordance with the increase of water production in each completion of the well due to high permeability, which causes the water movement to be different in each layer.



(a) (b)

Figure 6: Curves of WCUT for each valve over time for one producer well (P-1) (a) reactive; (b) proactive

Optimization Process

Figure 7 shows the results of the optimization process, which achieves stability faster for the CW and the IW with reactive control, with a total of 4 variables, than with proactive control. To optimize proactive control, five variables are needed, one for each valve, for a total of 20 variables, for the four wells. From the graph, it can also be seen that the parameters of the evolutionary algorithm chosen are sufficient to achieve the convergence for a good solution. However, it should be noted that the large number of simulations were performed for research purposes, since the graph shows that 1500 simulations are sufficient to demonstrate the advantage of the proactive control in relation to the reactive.

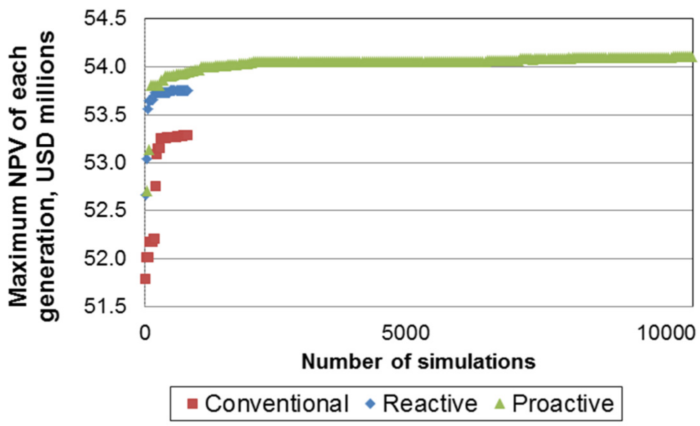


Figure 7: Number of simulations required to achieve the maximum NPV of each generation for a CW and for the two types of control of an IW, Case 2, and probable economic scenario

Figure 8 shows the graphs of NPV versus oil and water production for both types of control in an IW, respectively. The solution with the highest NPV and the corresponding oil and water production can be seen. The best solution for maximum NPV (optimal or suboptimal) does not always correspond to highest oil production or lowest water production. Depending on the objectives of the company, the manager can choose a solution with a slightly lower NPV that produces less water, for example.

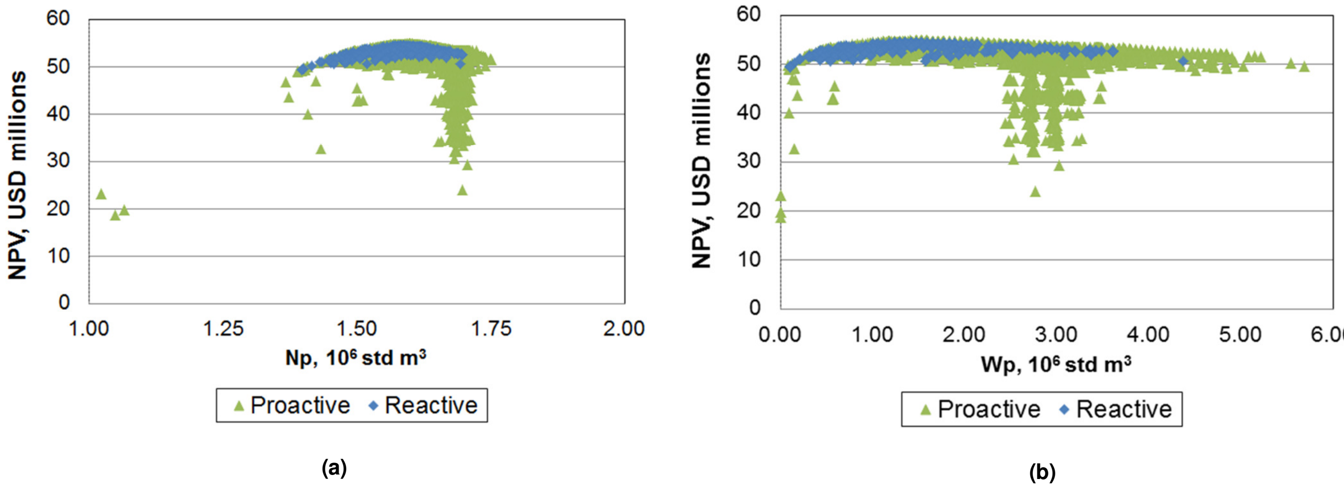


Figure 8: Graphs of (a) NPV versus oil and (b) water production for the probable economic scenario of Case 2 for the two types of IW control

Pessimistic and Optimistic Economic Scenarios of Case 2

Pessimistic Scenario

Table 11 presents the results for the pessimistic scenario, for low oil price and high cost of water production. Because of this unfavorable scenario, the most profitable solution would be low water production, leading to early closure of the well and, consequently, the decrease in total water production (and total oil production). As said before, it can be seen that the IW with both types of control can enhance oil recovery and increase the NPV even in adverse economic conditions.

Table 11: Production for a CW and an IW for the pessimistic scenario

Pessimistic Scenario	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.47	0.51	2.48	1.18	0
Intelligent - Reactive	1.49	0.52	2.52	1.27	0.09
Intelligent - Proactive	1.49	0.49	2.49	1.41	0.23

Table 12 shows that the proactive control increased the oil production and NPV and also reduced the water production when compared to a CW, providing the best performance for an IW. Also noteworthy is the large percentage increase of the NPV. As the water production is being penalized by the high cost of production, an IW is better able to control the water production than a CW for reasons already cited. However, it also should be noted that, because of the lower production of this case, the percentage increases become larger.

Table 12: Percentage differences between a CW and an IW for the pessimistic scenario

Pessimistic Scenario	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	+ 1.40 %	+ 2.00 %	+ 1.53 %	+ 7.44 %
Intelligent - Proactive	+ 1.26 %	- 3.83 %	+ 0.26 %	+ 16.55 %

Figure 9 shows the results of production. In the first graph, the closing of the IW with reactive control occurs before that of the CW and the proactive control closes slightly after the CW. These results show that the solutions are probably suboptimal because the reactive and proactive controls should close after the CW and not before, as in the reactive, and not slightly after, as in the proactive. This emphasizes the fact that the evolutionary algorithm is a good global optimizer but finds great difficulty in local optimization.

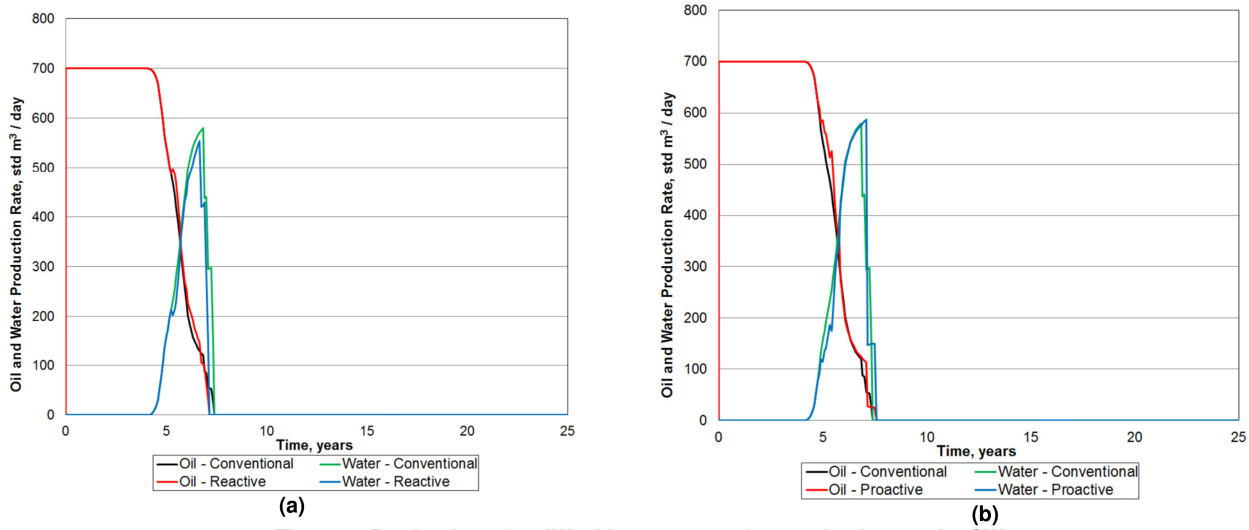


Figure 9: Production of an IW with two types of control valves and a CW

Figure 10 shows the time at which each valve closes. It should be observed that, as the scenario is unfavorable, the valves close earlier than those in the probable scenario and the differences in their closing times decline.

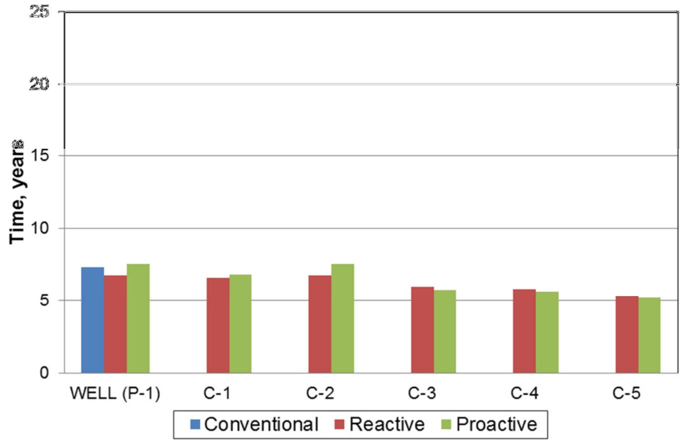


Figure 10: Closing valves for an IW (completions C1 to C5) and a CW (well) (P-1)

Figure 11 shows the increase in water cut on each valve for this economic scenario, according to the advance of the water in each sector of the well.

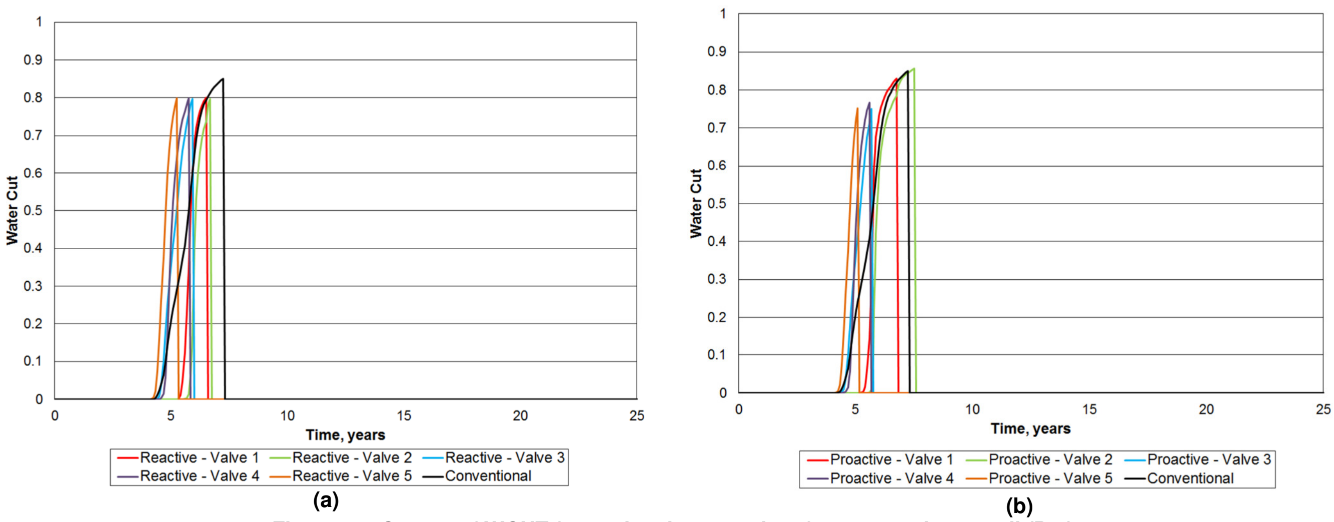


Figure 11: Curves of WCUT for each valve over time for one producer well (P-1)

Optimistic Scenario

Table 13 presents the results of the optimistic scenario for high oil price and low cost of water production. Due to this favorable scenario, the best solution is higher oil production than probabilistic and probable scenarios. For this case, it can also be seen that the IW with proactive control increases the NPV more than reactive control, as expected.

Table 13: Results of production for a CW and an IW for the optimistic scenario

Optimistic Scenario	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.65	2.95	5.17	107.04	0
Intelligent - Reactive	1.66	2.62	4.85	107.73	0.69
Intelligent - Proactive	1.68	2.93	5.17	108.51	1.46

Table 14 shows the percentage differences of an IW when compared to a CW.

Table 14: Percentage differences between a CW and an IW for the optimistic scenario

Optimistic Scenario	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	+ 0.53 %	- 12.54 %	- 6.53 %	+ 0.64 %
Intelligent - Proactive	+ 1.38 %	- 0.79 %	0.15 %	+ 1.35 %

Figure 12 shows the curves of the four production wells. The graphs show that some ICVs with both types of control closed early to avoid a high water rate and to increase the oil rate.

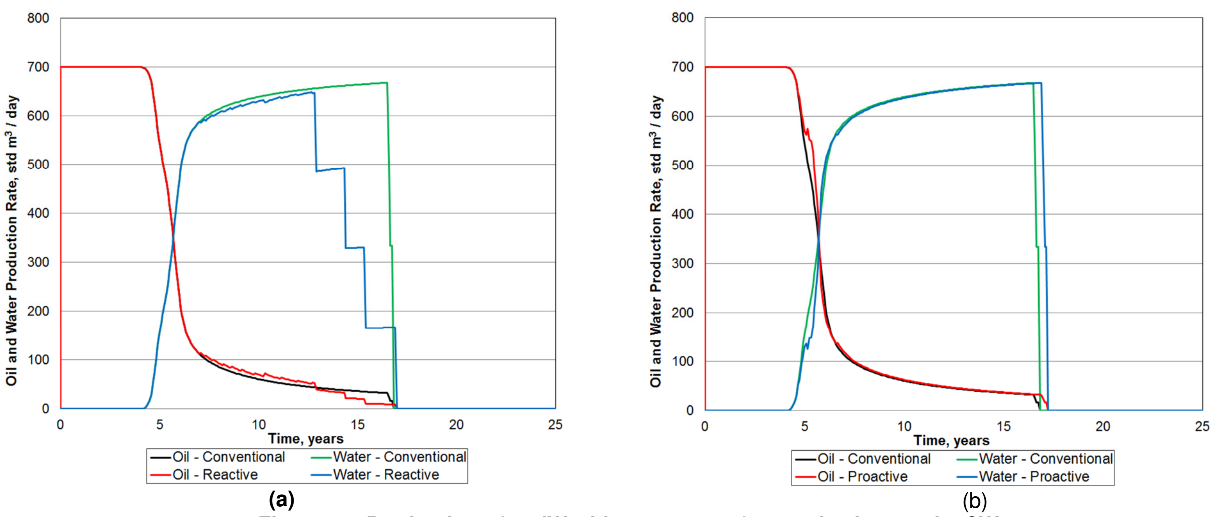


Figure 12: Production of an IW with two types of control valves and a CW

Figure 13 shows the time at which each valve closed for this optimistic scenario for producer well P-1. Observe that with reactive control the IW closes after the CW and the IW with proactive control closes after the IW with reactive control.

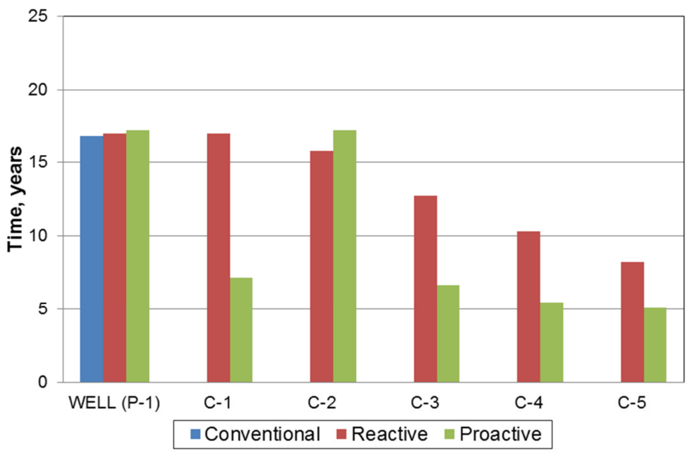


Figure 13: Closing valves for an IW (completions C1 to C5) and a CW (well) (P-1)

Figure 14 shows the increase in water cut on each valve for this economic scenario for well P-1. In Figure 12 (a), it can also be seen that the closure of each ICV occurred at very different times in the first graph.The second graph shows that the later closing of the second valve was due to high productivity. For both types of control, all valves are closed after the CW and the NPV has increased.

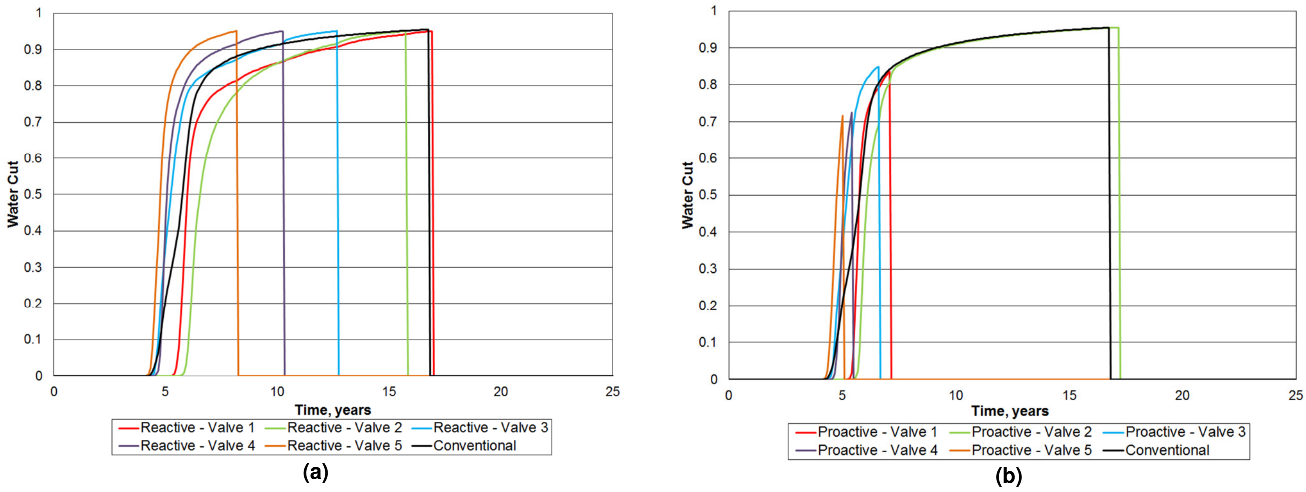


Figure 14: Curves of WCUT for each valve over time for one producer well (P-1) (a) reactive; (b) proactive

Comparison between Cases 1 and 3

Pessimistic Economic Scenario

Table 15 presents the results for the pessimistic scenario for Cases 1 and 3, remembering that Case 1 represents low heterogeneity and light oil and Case 3, higher heterogeneity and heavy oil. It can be seen that, even for these two cases, the IWs are able to increase oil production and NPV, except for Case 3 with reactive control, where oil production is almost identical to that of the CW. It is important to highlight the negative NPV for the case of heavy oil, because revenue is not enough to cover the initial investment.

Table 15: Production for a CW and an IW for the pessimistic scenario

Case 1	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.47	0.45	2.42	1.56	0
Intelligent - Reactive	1.48	0.46	2.44	1.08	- 0.48
Intelligent - Proactive	1.48	0.47	2.45	1.12	- 0.44
Case 3	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.13	0.72	2.00	-14.60	0
Intelligent - Reactive	1.13	0.57	1.84	-14.46	0.14
Intelligent - Proactive	1.16	0.73	2.04	-14.07	0.53

Table 16 shows the percentage differences between wells. As shown for Case 1, the IWs are not advantageous due to less heterogeneity. As for Case 3, it is shown to be capable of increasing NPV for both types of control.

Table 16: Percentage differences between a CW and an IW for the pessimistic scenario

Case 1	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	+ 0.43 %	+ 3.33 %	+ 0.88 %	- 44.22 %
Intelligent - Proactive	+ 0.61 %	+ 5.64 %	+ 1.50 %	- 38.76 %
Case 3	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	- 0.44%	- 27.19 %	- 8.70 %	+ 0.93 %
Intelligent - Proactive	+ 2.46 %	+ 0.48 %	+ 1.75 %	+ 3.73 %

Probable Economic Scenario

Table 17 presents the results for the probable scenario. It should be noted that Case 1 has practically the same oil production, leading to a negative NPV. This is because of the Case with less heterogeneity, causing the water to flow evenly throughout the well. As for Case 3, an IW works better than a CW due to the increase in the heterogeneity of the model.

Table 17: Production for a CW and an IW for the probable scenario

Case 1	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.58	1.49	3.60	53.80	0
Intelligent - Reactive	1.58	1.43	3.54	53.34	- 0.46
Intelligent - Proactive	1.58	1.43	3.54	53.29	- 0.51
Case 3	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.22	1.59	2.97	27.98	0
Intelligent - Reactive	1.23	1.52	2.91	27.97	- 0.01
Intelligent - Proactive	1.23	1.45	2.85	28.72	0.74

Table 18 shows the percentage differences between wells. The IW with proactive control in Case 3 should be highlighted.

Table 18: Percentage differences between a CW and an IW for the probable scenario

Case 1	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	- 0.08 %	- 4.39 %	- 1.81 %	- 0.86 %
Intelligent - Proactive	- 0.14 %	- 4.32 %	- 1.82 %	- 0.95 %
Case 3	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	+ 0.55 %	- 4.65 %	- 2.16 %	- 0.02 %
Intelligent - Proactive	+ 0.71 %	- 9.39 %	- 4.45 %	+ 2.60 %

Optimistic Economic Scenario

Table 19 shows the results for the optimistic scenario. It can be seen that in Case 1, the IWs present practically the same results as the CW for the same reason mentioned above. In Case 3, the IW has better performance with proactive control, with an increase in NPV and even a decrease in water production.

Table 19: Production for a CW and an IW for the optimistic scenario

Case 1	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.65	2.82	5.04	107.65	0
Intelligent - Reactive	1.65	2.70	4.91	107.15	- 0.50
Intelligent - Proactive	1.65	2.75	4.96	107.34	- 0.31
Case 3	*Oil Production (10^6 std m^3)*	*Water Production (10^6 std m^3)*	*Water Injection (10^6 std m^3)*	*NPV (USD millions)*	*Δ NPV (USD millions)*
Conventional	1.28	2.56	4.00	71.69	0
Intelligent - Reactive	1.28	2.30	3.75	71.68	- 0.01
Intelligent - Proactive	1.29	2.48	3.94	72.84	1.15

Table 20 shows the percentage differences between wells, which should be highlighted for proactive control in Case 3

Table 20: Percentage differences between a CW and a IW for the optimistic scenario

Case 1	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	- 0.18 %	- 4.62 %	- 2.62 %	- 0.46 %
Intelligent - Proactive	+ 0.04 %	- 2.83 %	- 1.64 %	- 0.29 %
Case 3	*Oil Production*	*Water Production*	*Water Injection*	*NPV*
Intelligent - Reactive	- 0.08 %	- 11.05 %	- 6.82 %	- 0.01 %
Intelligent - Proactive	+ 0.93 %	- 3.06 %	- 1.58 %	+ 1.57 %

Economic Uncertainty and Decision Analysis

For the previous results, the ΔEMV is calculated for all cases studied, as shown on Table 21 below:

Table 21: ΔEMV for three case studies for both types of control

	Reactive Control	*Proactive Control*
	EMV (USD millions)	*EMV (USD millions)*
Case 1	- 0.48	- 0.44
Case 2	0.42	0.83
Case 3	0.03	0.79

Table 21 above could help in making a decision between an IW and a CW. Since, in this work, an intelligent completion with five valves costs USD 625,000, it would not be indicated for Case 1, but it could be profitable in Case 2, for both types of control. As for Case 3, it would be advantageous for proactive control.

Conclusions

The results show that the IW with reactive control is better than the CW, shown to be advantageous to make an additional investment in intelligent completion. The IW with proactive control led to better results than reactive control in maximizing the field's NPV, as expected. The graph obtained in the optimization process leads us to conclude that, since the beginning of the process, the proactive control provides better results than the reactive control. The evolutionary algorithm used in the optimization process proved to be an efficient global optimizer but encountered some difficulties in local optimization, which may be solved by a manual optimization or use of a local optimization method. The best results were obtained in the case with an heterogeneous reservoir and light oil. The results also indicate that the use of an IW in cases of heavy oil may not be equally advantageous, depending on the type of control to be used. This can be explained by the fact that the water has greater mobility in relation to oil in cases in which the oil is heavier. These results were generated for deterministic cases (especially without geological uncertainty). This implies that the differences between an IW and a CW may be improved, due to the fact that an IW has a high operational flexibility to attend the uncertainties involved in the process. It may also be noted that, under economic uncertainty, IWs with proactive control were better than the IWs with reactive control, and these were better than the CWs.

Nomenclature

BHP – Bottom Hole Pressure
CW – Conventional Well
EMV - Expected Monetary Value
ICV – Inflow Control Valves
IW – Intelligent Well
NPV – Net Present Value
WCUT – Water Cut

Acknowledgments

The authors would like to thank Baker Hughes, CNPq, Petrobras, UNISIM and Cepetro for supporting this research and development project.

References

Addiego-Guevara, E. A.; Jackson, M. D.; Giddins, M. A.; Insurance Value of Intelligent Well Technology against Reservoir Uncertainty, SPE 113918, 2008 SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, April, 2008.

Baeck, T.; Fogel, D.B.; Michalewicz, Z.; Evolutionary Computation. IOP Publishing, UK, 2000.

Ebadi, F.; Davies, D. R.; Should "Proactive" or "Reactive" Control Be Chosen for Intelligent Well Management? SPE 99929, 2006 SPE Intelligent Energy Conference and Exhibition, Amsterdam, Netherlands, April, 2006.

Kharghoria, A.; Zhang, F.; LI, R., Jalali, Y.; Application of Distributed Electrical Measurements and Inflow Control in Horizontal Wells under Bottom-Water Drive. SPE 78275, 2002 SPE 13th European Petroleum Conference, Aberdeen, Scotland, October, 2002.

Sarma, P.; Aziz, K.; Durlofsky, L. J.; Implementation of Adjoint Solution for Optimal Control of Smart Wells. SPE 92864, 2005 SPE Reservoir Simulation Symposium, Houston, Texas, USA, February, 2005.

Van Essen, G. M.; Jansen, J. D.; Brouwer, D. R.; Douma, S. G.; Rollett, K. I.; Harris, D. P.; Optimization of Smart Wells in the St. Joseph Field. SPE 123563, 2009 SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, August, 2009.

Yeten, B.; Durlofsky, L. J.; Aziz, K.; Optimization of Smart Well Control. SPE 79031, 2002 SPE/PS-CIM/CHOA International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference, Calgary, Alberta, Canada, 2002.

Yeten, B.; Brouwer, D. R; Durlofsky, L. J.; Aziz, K.; Decision Analysis under Uncertainty for Smart Well Deployment, Journal of Petroleum Science & Engineering, Elsevier, Amsterdam, 43 (2004) 183 -19.