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FlexWell: smart wells flexibility management and valuation under uncertainty

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Abstract

Smart well, or intelligent well completion, is an oilfield development technology operated remotely from the platform that, in real time, monitor (bottom-hole sensors) and control (bottom-hole valves) oil/gas/water production and water/gas injection by reservoir zone. Although more expensive, this well technology enables the acquisition of relevant information (learning option) and inject flexibility in the development plan because we can manage (exercise options) to open or close the downhole valves in response to new geological information arriving continuously during the oilfield life. The valuation of smart well technology shall consider the geological and market uncertainties as well as the technology reliability. This complex investment under uncertainty problem, in which information acquisition and flexibility are the primary sources of value, demand sophisticated methods of optimization under uncertainty. In this paper, we describe the valuation of this flexibility using a new decision support system under development called FlexWell. The main FlexWell goal is to assist the experts in drawing up reservoir development plans with smart wells, valuating the benefits from the extra flexibility provided by a more capital intensive technology. FlexWell's methodology is based on approximated dynamic programming (Powell, 2011), which reduce the computational burden, and on reservoir simulation, to evaluate the flow control strategy for smart wells management over various possible reservoir scenarios. The smart wells investment attractiveness rises with the volatile oil price. Here we consider the oil price uncertainty in a conceptual real options model to decide between the cheaper traditional completion and the more expensive intelligent completion investments. The main inputs for option model come from the FlexWell, so that both level of real options values are integrated.

Keywords: exploration & production of petroleum, smart well, value of flexibility, real options, investment under uncertainty, geological uncertainty, value of information, learning options, reservoir management.

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1. Introduction and literature review

In recent years, new technologies and concepts have been developed and deployed to maintain the profitability of oilfield development; among them, Smart Well Technology (also called Intelligent Completion Well Technology) is one of the most significant breakthroughs (Gao et al., 2007). Since the first intelligent completion[2], installed in August 1997 at Saga's Snorre Tension Leg Platform in the North Sea (Gao et al., 2007), smart wells have added a new dimension to commercial analysis in the oil sector (Mathieson et al., 2003) and the technology application has increased exponentially (Alsyed & Yateem, 2012) mainly in the high oil prices period. However, as pointed out by Glandt (2005), implementation of any new technology in the E&P industry requires a solid business case that clearly demonstrates its incremental value, proving the importance of an optimal technology management.

Smart well technology is an innovative system that can be summarized as a combination of (Armstrong & Jackson, 2001): downhole sensors for sampling environmental parameters, downhole actuators (valves) for changing the operating conditions of well and interpretation, and processing algorithms for optimizing reservoir/well performance.

The controlling capability (flexibility) is achieved by using hydraulic, electric or electro-hydraulic controlled devices (Ajayi & Konopczynski, 2003) (Sakowski et al., 2005), that are used to regulate the flow into the wellbore. The valves can either be binary on/off system (only open and closed) or have variable chocking capability (Akram et al., 2001). The open or closed control in which the controls only operate on the extremes is called 'bang-bang' control (e.g., Brouwer & Jansen, 2002). These control devices are called Inflow Control Valves (ICV's) (Brouwer & Jansen, 2002) (Glandt, 2005) (Van der Steen, 2006) (Kavle et al., 2006) (Leemhuis et al., 2007); Flow Control Valves (FCV's) (Van der Steen, 2006); Interval Control Valves (ICV's) (Armstrong & Jackson, 2001) (Akram et al., 2001) (Han, 2003) (Ajayi & Konopczynski, 2003) (Ajayi & Konopczynski, 2005) (Aggrey et al., 2006).

As noted by Esmaiel (2005), "*One of the primary values of the smart well is in its flexibility. This value can be quantified with Real Options*". The real options (RO) literature (Tourinho, 1979; Dixit & Pindyck, 1994; Trigeorgis, 1996) is nowadays much consolidated and so the RO literature

[2] Well completion is the activity of making a well ready for production (or injection) by installing the tubing (production column), an assembly of valves named Christmas tree, and other equipment inside the well. When including bottom hole sensors and remotely operated bottom hole valves, we call intelligent completion.

applied to petroleum investments (e.g., Paddock, Siegel and Smith, 1988; Dias, 2004; McCormack and Sick, 2001).

However, in this very complex application of smart wells, a realistic and transparent real options model is a job to be done. Given the geological complexity of oil reservoirs and its uncertain behavior along the time, the valuation of smart wells with real options are still in infancy, with the proposed models perhaps still too simplified. Han et al. (2002) identify two main value components that drive the smart well option value. First, the *uncertain component*, from the variance of the asset value around the expected value, a value derived from the reduction of uncertainty around this mean values. Second, the *jump component*, from the variance of the jump process in the asset value caused by the smart well (increase in production and/or recoverable oil, plus well intervention cost savings). Han (2003) uses a real options valuation with a “WellDynamics' proprietary approach”, but the article does not give sufficient details to analyze their option approach. None of these articles analyze the interaction of geological uncertainties with market uncertainties. Most papers focus only in the geological uncertainty, although the intuition tells that the oil price level and its uncertainty can be very important to justify or not the more expensive well completion technology, because most of the benefits are associated with the increased revenue from oil production. In this paper, we show that the oil price level and its uncertainty are very important to decide to adopt or not the intelligent completion technology.

Professional petroleum literature list many benefits provided by the use of smart well technology. Examples are Armstrong & Jackson (2001), Yeten et al. (2002), Ajayi & Konopczynski (2003), Han (2003), Han et al. (2002), Konopczynski et al. (2003), Chukwueke & Constantine (2004), Sakowski et al. (2005), Leemhuis et al. (2007), Ajayi et al. (2008), Almeida et al. (2010), Abreu et al. (2014), Abreu et al. (2015). We talk about some benefits in the section 2.

One of the challenges of smart well deployment is the inability to properly manage and quantify the value generated by the flexibility under uncertainties. In general, the greater the uncertainty, the greater the value of flexibility. But the traditional NPV approach in general sub-estimate the flexibility value because looks only expected cash flows, without capturing the options that can be exercise in different possible realizations of the uncertainty. Real options valuation is a tool designed to capture the flexibility value under uncertainties, but the complexity of this dynamic problem with market and geological uncertainties makes the existent models still too simplified, as pointed out above.

Other challenge with smart wells is the uncertainty related with the technology reliability, due to the possible loss of the smart system's ability to function properly and to meet the required reservoir or well management objectives (Aggrey & Davies, 2007). Completion failures reduce the field's total profitability through decreased revenue (decreased system availability) and/or increased operational expenditures (OPEX) due to well interventions (more workover cost). Consequently, when moving into deeper water, the economic penalty for delayed/lost production from the system failure becomes greater (Brownlee et al., 2001). Furthermore, subsea well system repairs and interventions also become more expensive and are associated with longer delays due to availability and mobilization times for the required repair rigs and vessels (Brownlee et al., 2001). So, how can the smart wells be valued whilst balancing their benefits with their challenges? This challenge is the energy that moves the FlexWell project, a joint research of PUC-Rio and Petrobras' Research Center (CENPES).

2. Conventional versus Intelligent Completion investments by real options lens

There are at least two levels of real options analysis for smart wells/intelligent completion. One is the decision to develop the oilfield[3] with cheaper conventional completion or with more expensive intelligent completion, a less mature technology but with higher revenue potential. The other real option level of analysis is related with the flexibility to open and close valves, with continuous arriving of geological/reservoir information, that is, with the benefit of this technology: information and flexibility to optimize the oilfield exploitation. Of course the two levels are linked: we need to quantify the intrinsic flexibility benefits of this technology in order to decide if invest in the conventional or in the new technology. In this section, we focus in the first level. In the next two sections, we will talk about the other level and the FlexWell project.

The oilfield development with smart wells has higher investment cost than the development with conventional wells. Let I_1 be the development investment with conventional wells and I_2 with smart wells, with $I_2 > I_1$. Let V_1 and V_2 be the developed reserve value[4] with conventional and intelligent completion, respectively. In this simple setting, the NPVs from the exercise of one of this option are:

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[3] Smart wells also can be used in gas field development. But generally oilfield is more attractive economically to use this technology.

[4] The developed reserve value (V) can be view as the present value of the petroleum production revenue net of operational costs and taxes. Here, this value incorporates the flexibility value and the value of information arising from the intelligent completion technology.

$$NPV_1 = V_1 - I_1 \quad (1)$$

$$NPV_2 = V_2 - I_2 \quad (2)$$

With $I_2 > I_1$ and $V_2 > V_1$ to make economic sense[5]. We have $V_2 > V_1$ due to the additional flexibility value embedded in the intelligent completion alternative. These values are function of the market condition, especially the oil price P, which is stochastic.

There are many benefits associated with smart wells, most of them are increasing function of the oil price. Some examples:

a) Reservoir with multiples production zones. With smart wells we can exercise the option to change the production from one zone to other without cost (only closing one valve and opening other). In the conventional completion, this option is much more expensive (and could be not economic), because we need to send an expensive rig to enter in the well to switch the production zone. In addition, even being still economic, the rig could not be available for months, delaying the additional oil production from this switch zone option.

b) Prevention of gas and water cones in wells by adjusting the bottom hole valves (e.g., we can close partially or totally the lower zones of the reservoir reducing the water production). This not only reduces the water treatment cost, but improved the oil recuperation factor and can generate some additional options (next item).

c) The reduction of water production with the smart well technology releases capacity to the liquid in the platform. Production platforms in mature oilfields are generally limited to liquid (oil + water) capacity: the decline of oil production along the time is accompanied by the increase of the water production. In this case, we don't have the option to drill another well to increase the production due to platform constrain. With smart well, reducing the water cut, the free capacity allows to consider the infill drilling investment to rise the production.

d) We can reduce the workover costs (cost of well maintenance), by closing one zone with problem and opening other zone. Without intelligent completion, we need to stop the zone with problem and wait for a (expensive) rig to change the zone. Production can stop for months or even could be not feasible to pay the rig cost to switch the zones.

[5] In some cases with multiple zones, smart wells can reduce the quantity of wells required for the oilfield exploitation, because the same well can exploit more than one zone. If the economy of number of wells is more important than the additional cost per smart well, so that $I_2 \leq I_1$, we have a case of clear advantage for smart wells development and could be unnecessary additional analysis for the decision if we assume $V_2 > V_1$.

The value of developed reserve is a function of the oil prices. We can draw the chart NPV x P from the oilfield development with either conventional or intelligent completion. Let us work with a parametric NPV equation. For concession fiscal regime in the oil sector, this chart is linear. For production sharing fiscal regimes, this chart is not linear (NPV is concave with P). Here we focus in the concession/linear NPV(P), but the extension to production sharing is straightforward. We present below two linear models, one is the "Business Model" and the other is the "Rigid Cash Flow Model"[6]. The value of the developed reserve is a function of the oil price (P), the reserve volume (B, as the number of barrels) and the economic quality of the reserve (q, related with the productivity of the reserve, see below). The Business Model equation is:

$$V_i = q_i\, B_i\, P\ ,\ \text{ with } i = 1, 2 \qquad (3)$$

The Rigid Cash Flow Model is also linear, but highlights the fixed operational cost C:

$$V_i = q_i'\, B_i\, P - C\ \ ,\ \text{ with } i = 1, 2 \qquad (4)$$

In the Business Model all the operational cost is embedded in the quality q. So, q > q' for the same cash flow parameterization. Figure 1 plots the NPVs from these two linear models:

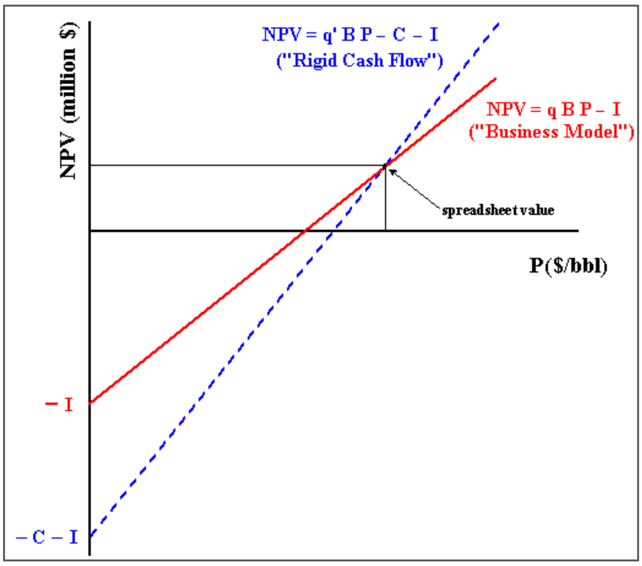

Figure 1 – Two Linear Parametric NPV x P Models

The Business Model is simpler and is less sensitive to oil price changes (more conservative for option valuation). We adopt the Business Model here. When comparing intelligent completion (CI) with conventional completion, CI shall have higher quality q and higher B than with conventional

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[6] See details at http://marcoagd.usuarios.rdc.puc-rio.br/payoff_model.html or in Dias (2014, chapter 1) and Dias (2015, appendix IV-D).

technology. The better production profile from CI alternative implies in higher speed of oil production so that the present value of revenues is higher. In addition, CI allows higher reservoir recovery factor, so that the reserve volume B under CI shall be higher than with the non-flexible technology[7].

Figure 2 shows the NPV x P chart for the two mutually exclusive development alternatives, intelligent and conventional completion, considering $I_2 > I_1$, $q_2 > q_1$ and $B_2 > B_1$:

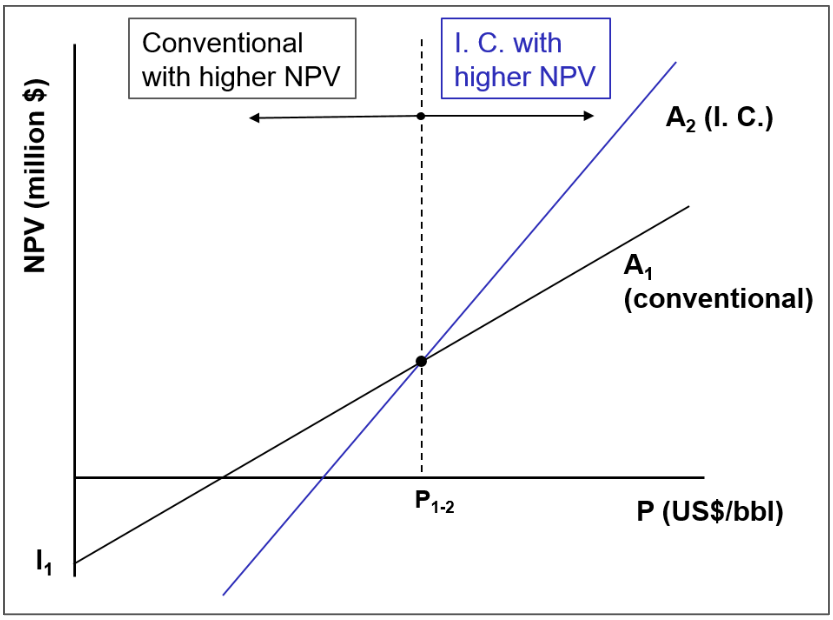

Figure 2 – NPV versus Price for Conventional and Intelligent Completions

Figure 2 shows that the NPV x P line for IC alternative has higher inclination than conventional completion alternative. It is easy to see that the inclination of $NPV_i = q_i\ B_i\ P - I_i$ is equal $q_i\ B_i$ and A_2 is more inclined because $q_2\ B_2 > q_1\ B_1$. Figure 2 also highlights the indifference oil price or break-even price $P_{1\text{-}2}$ of these alternatives (at $P_{1\text{-}2}$, conventional and intelligent completion have the same NPV). So this chart tells that the economic choice of conventional or intelligent completion depends on the oil price.

Imagine the oil price is a little bit *lower* than the indifference price $P_{1\text{-}2}$. By the Figure 2, we choose the conventional alternative. However, the oil price is stochastic, every day the price changes in the market. If we exercise the option to develop the oilfield with conventional completion and few weeks after the oil price rises inverting the NPV order, we could regret. So, we must consider the

[7] This can be significant. For example, an oilfield with 1 billion barrels in place with recovery factor (RF) of 30% has a reserve volume B_1 = 300 million bbl. If we increase the RF in 6% (to 36%) with smart wells, the new reserve volume is B_2 = 360 million bbl. So, an increase of 6% in RF increases the reserve volume in 20%.

defer option before exercising the higher payoff alternative. We can wait for higher oil price in which is optimal to exercise the more capital intensive alternative (with intelligent completion). So, the rule invest in the conventional alternative (A_1) if $P < P_{1-2}$ is valid only if it is a now-or-never opportunity. If it is not the case (we can wait), the defer option must be considered, and the defer option increases with the market volatility.

Defer option is the most traditional real option, analyzed in classic papers like McDonald and Siegel (1986). Here we have a finite lived (not perpetual) option, because in petroleum sector there is a maximum date to commit the development investment. The period of exploratory phase is typically between 5 and 10 years. At the expiration, or we declare the oilfield commercial and commit an investment plan or the discovered oilfield (or tract without discoveries) must return to Government Petroleum Agency.

For the defer option we can consider different stochastic models for the oil price. Here, for simplicity, we use the popular Geometric Brownian Motion (GBM) model, given by[8]:

$$dP = \alpha\, P\, dt + \sigma\, P\, dz \tag{5}$$

Given the current $P(t = 0) = P$, where α is the drift rate (expected growth rate of P), σ is the volatility (standard deviation of P return), dz ($= N(0, 1)\sqrt{dt}$) is the standard Wiener increment[9].

This conventional x intelligent completions dilemma is a problem of choice of intensity (or scale) of investment considering the option to postpone (defer) the investment, waiting for better market condition to exercise the option. This is an American type real option (we can exercise in any time up to expiration). The real options literature on optimal scale with discrete alternatives has been analyzed in the real options literature (Dias, 2004; Décamps & Mariotti & Villeneuve, 2006, and Dias, 2015, chapter 27). Following Dias (2015), we use the *variational inequalities* approach (Bensoussan and Lions, 1978) for this American option problem to generate the possible *disconnected exercise regions* of oil price (see below) for the two completion alternatives. In this way, there are two possible charts Option Value x Oil Price, depending on the volatility. Figure 3 shows the case with higher volatility.

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[8] A more realistic stochastic oil price model shall include *mean reversion* and *jumps* features such as the Marlim Model: see http://marcoagd.usuarios.rdc.puc-rio.br/sim_stoc_proc.html#mc-mrj or Dias (2015, p.144).

[9] See Dixit & Pindyck (1994), Trigeorgis (1996) or Dias (2015) for details.

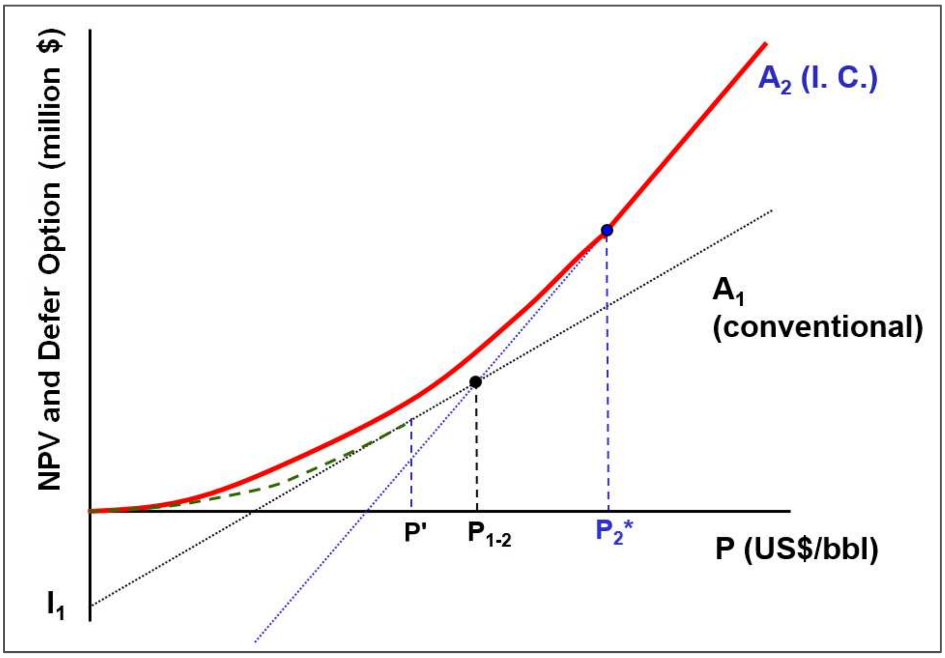

Figure 3 – Defer Option x Price and the I.C. Threshold

The oil price threshold to exercise the option to develop the oilfield is the point in which the wait value (red curve) tangency the option exercise payoff (the NPV). In Figure 3, in some date t before the expiration T, the only point that the defer option value is the threshold P_2*. So, in this case, the optimal decision rule is: wait and see if $P < P_2$*; exercise the alternative A_2 (intelligent completion) if $P \geq P_2$*. Here, at this date $t < T$, is not optimal to exercise the conventional alternative (A_1). The point P' showed in Figure 3 is not a threshold to exercise A_1: the dotted line curve is the defer option value only when A_1 is the unique alternative to develop the oilfield, but this is not the case: it is more valuable to wait (with chance of exercise A_2 if the oil price rises) than exercising A_1. With the passage of time, the option curve (red line) drops and the red line will have two points of tangency, one for alternative A_1 and other for alternative A_2. See below.

If the volatility is lower or when we are approaching expiration, appears an exercise region for the alternative A_1 (conventional completion), as illustrated in Figure 4.

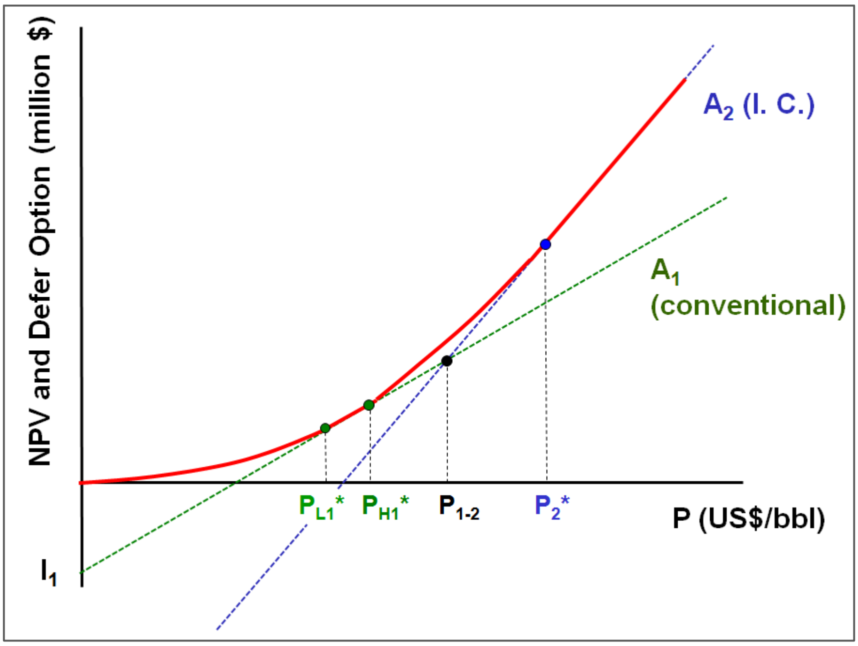

Figure 4 – Defer Option x Price with Lower Volatility or Near Expiration

Figure 4 illustrate the decision rule: if the oil prices is lower than P_{L1}*, the optimal is to wait and see; if the oil price P is in the interval $P_{L1}^* \leq P \leq P_{H1}^*$, it is optimal to exercise immediately the conventional alternative (A_1); if the oil price is in the open interval (P_{H1}*, P_2*) it is optimal to wait and see; and if the oil price is equal or higher than P_2*, the optimal is the immediate exercise of the IC alternative (A_2).

So, in Figure 4 case there are two disconnected exercise regions: the interval [P_{L1}*, P_{H1}*] for the conventional alternative A_1 and the interval [P_2*, ∞) for the IC alternative A_2. Between these exercise intervals, there is an intermediate waiting region (P_{H1}*, P_2*). If the oil price is inside this intermediate waiting interval, the optimal is to wait or the price to move above (to exercise A_2) or to move below (to exercise A_1).

This model captures the optimal well technology choice under market uncertainty, and although demands numerical methods (e.g., finite differences) so solve partial differential equation in the variational inequalities context, this is clear and consolidate approach in real options theory.

The higher challenge is to calculate to value of flexibility with and without intelligent completion, to estimate the NPV(P) function for each alternative. In our example, we need the economic quality of the reserve q and the reserve volume B improved by smart wells in order to decide the investment in this technology or not. This is one important objective of the FlexWell project and the methodology we summarize in the next two sections.

3. Smart wells management by flow control strategies

To reach an informed decision regarding the deployment of smart wells, one must first quantify its benefits from the optimal smart wells management. The benefits of these wells can be determined through the optimization of the expanded[10] net present value (NPV) under uncertainty, although some authors focus in maximizing the reservoir recovery factor (Yeten et al., 2004). For this reason, the process of optimization of the flow control strategy from smart completions has interested the area of petroleum reservoir development and management.

The flow control strategy optimization for a reservoir with known properties (deterministic optimization) is already a challenging operational research problem, which aims to find the optimal settings for the control valves of the smart wells. This optimization becomes more complex when the reservoir properties are uncertain, since for each potential valve setting a forecast obtained through a potentially expensive reservoir simulator, for each of the possible reservoir scenarios, is required. Although this significantly increases the optimization time, the results are more robust for reservoir uncertainty because they consider the potential outcomes over several scenarios.

Despite the uncertainties related to the reservoir's geological characteristics, some optimization strategies consider uncertainty fully resolved before any decision needs to be made concerning the flow control strategy. But it is risky to develop a control strategy based on the predictions of a model that is unlikely to capture true reservoir behavior. Furthermore, since the acquisition of information can reduce the geological uncertainties, considering information during the strategy definition allows one to make more certain decisions when choosing the valve settings. Many studies recognize the problem of incorporating reservoir uncertainties in the optimization workflow. Nevertheless, the optimization strategies can still be made considering the geological uncertainties but ignoring the information in some level, as we describe later.

There are three main attributes/techniques that are able to reduce the challenge of operating under uncertainty: robustness of solutions; acquisition of information; and flexibility of solutions. All three of these should play an important role in reservoir management (Moczydlower et al., 2012), but at times it is difficult to decide what method, or combination of methods, will minimize the primary/influential uncertainties more efficiently. For many flexible solutions, cost must be taken

[10] "Expanded" means that consider the flexibility and learning (information) values. The traditional NPV looks only the expected cash flows, not the flexibility value in different possible scenarios. Uncertainties make smart wells flexibility even more important economically. Expanded NPV is used also as synonymous of real option value (Trigeorgis, 1996).

into consideration: both direct, due to more expensive equipment and procedures, and indirect, caused by possible equipment failure.

In order to decide if the benefits provided by a particular reservoir management solution justifies its additional cost, we need to determine both an optimal strategy for the management of these technologies and a method to determine the additional value that they offer, e.g., increased/accelerated oil production and/or reduced water management costs.

4. Valuing with FlexWell the flexible management under uncertainty from smart wells

To aid the expert in finding the flow control strategy for smart wells and valuing its flexibility under geological uncertainties, we propose a decision support system, named FlexWell. In this paper, we intend to describe and demonstrate the proposed methodology, whose purpose is to value flexibility and manage the flow control strategy of smart wells under uncertainty conditions, reacting to future information as it is acquired in real time.

Figure 5 gives an overview of the FlexWell process, highlighting its multidisciplinary nature and the methods required in this I.C. support decision system project.

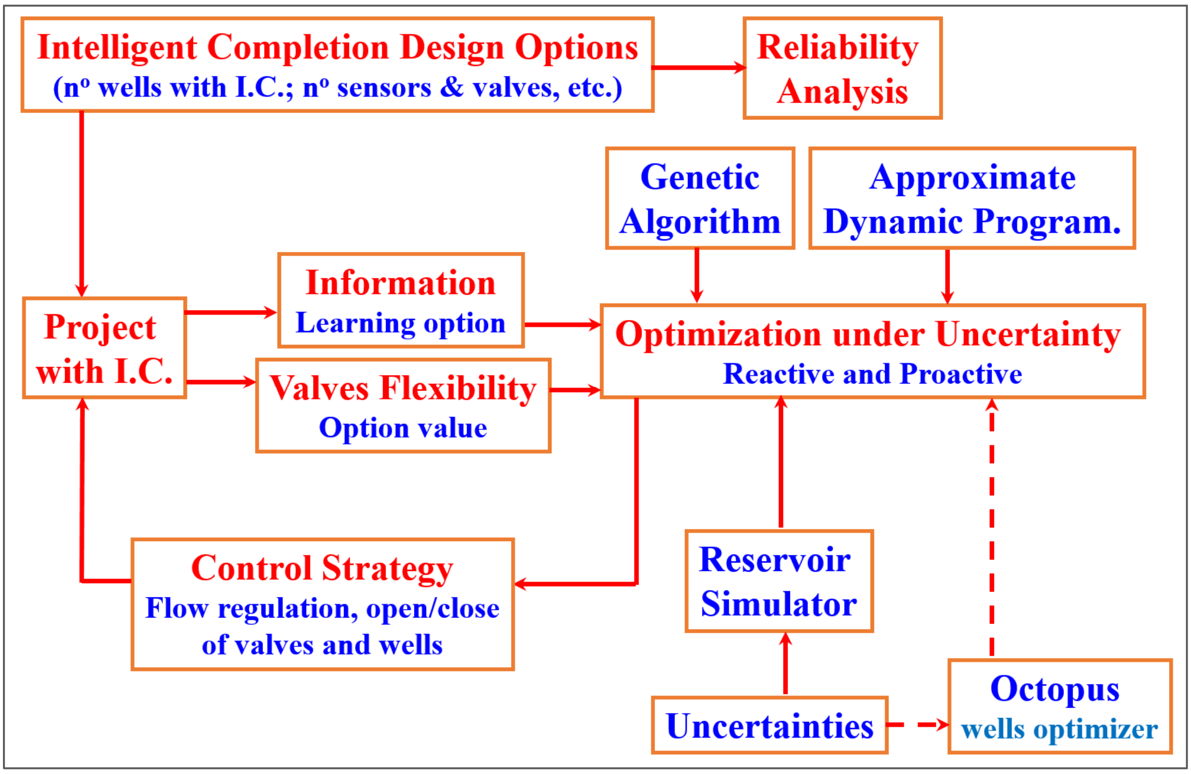

Figure 5 – FlexWell Process: Information, Flexibility and Optimization under Uncertainty

Figure 5 show that we need analyze many intelligent completion design options (top left), considering the number of valves and sensors, the number of wells with conventional and with I.C. completion, and other issues like type of valves (on-off, several positions, etc.). But it is also necessary to consider the reliability of each possible design schema. Low reliability cases increase the well maintenance cost (workover cost), the opposite of this technology promise. For each potential I.C. project, we shall quantify the value of information (learning option) and the value of the flexibility from the smart wells valves management. These are real option values obtained from optimization under uncertainty methods. For optimization we can use genetic algorithms[11] or approximate dynamic programming (Powell, 2011; Bertsekas, 2012). In this process, we must analyze many different control strategies of open-close valves, to regulate flow rate in each reservoir zone, etc. This process demands many reservoir simulations so that are necessary one or more reservoir simulators[12] to perform this computationally expensive job. Figure 5 (bottom right) also indicates one link to the support decision system named Octopus. This is an optimizer system to choose well location, number of production and injection wells, type of wells (vertical, horizontal, directional), which is planned to be integrate to FlexWell in order to help in part of optimization job required in the smart wells grid analysis.

The FlexWell's methodology is based on Abreu et al. (2015), combining the concepts of approximated dynamic programming, which reduces the computational burden, and on reservoir simulation (CMG, 2015), to evaluate the flow control strategy for smart wells management over various possible reservoir scenarios. Despite this methodology limits the flexibility somewhat so that not all the value of complete dynamic programming is retained – for instance, since the acquired information only affect the decision after it has been made, this policy will not remake the early decision to increase the future value. Those such losses are often small, and will be more than offset by the increased flexibility that can be feasibly simulated with this approximation.

It begins by optimizing the valve settings over all time, maximizing the expected NPV in the absence of future information. The expectation is made over a set of reservoir models representing the reservoir uncertainty. The valve settings can be adjusted at a discrete set of times. The result is the set of best settings, over all time steps, based only on what is known at time zero, i.e., this is the best proactive strategy.

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[11] See several genetic algorithms applications in petroleum exploration & production in Pacheco and. Vellasco (2009), including concepts of evolutionary real options for oilfield development investment decisions.

[12] Reservoir simulators are used by petroleum companies to generate production forecasts that are needed to help make investment decisions or to help reservoir management during the productive phase of the petroleum reservoir.

These settings are then applied to the entire set of reservoir models and future measurements are forecast for the next time step. We then proceed to the next time step, i.e., the next time at which valve adjustments are allowed. At this time, we incorporate the information forecast for each reservoir model, potentially reducing uncertainty. The procedure for including future information involves applying cluster analysis to the forecast measurements. The notion is that measurements falling within a common cluster are associated with models that are indistinguishable using only those measurements. In other words, the original set of models representing the prior uncertainty is partitioned into smaller sets of models that represent the uncertainty after assimilation of measurement data. This part of the methodology identifies when measurement data are informative. Within each cluster we have reduced uncertainty and should consider a change in valve settings going forward.

For each cluster of models, we determine a new optimal proactive strategy for the future valve settings (past valve settings are not adjusted). This creates a recursion in which an effective, and realizable, strategy can be obtained that keeps the benefits of both proactive and reactive strategies. Since this recursion is performed in the forward direction, the number of required simulations is exponentially reduced compared to the complete dynamic programming solution. Figure 6 shows a simplified decision workflow to implement the optimization strategy that considers both model uncertainty and future information. We provide an illustration of the first step of our optimization. The top part of Figure 6 has an illustration of the valuation of control valves with information. In this case with three decision points and two measurement points, corresponding to choosing the initial valve settings at time t0, and then possibly changing the valve settings at two future times, t1, t2. Measurements are also taken at times t1, t2, with the future valve settings chosen in light of this new information.

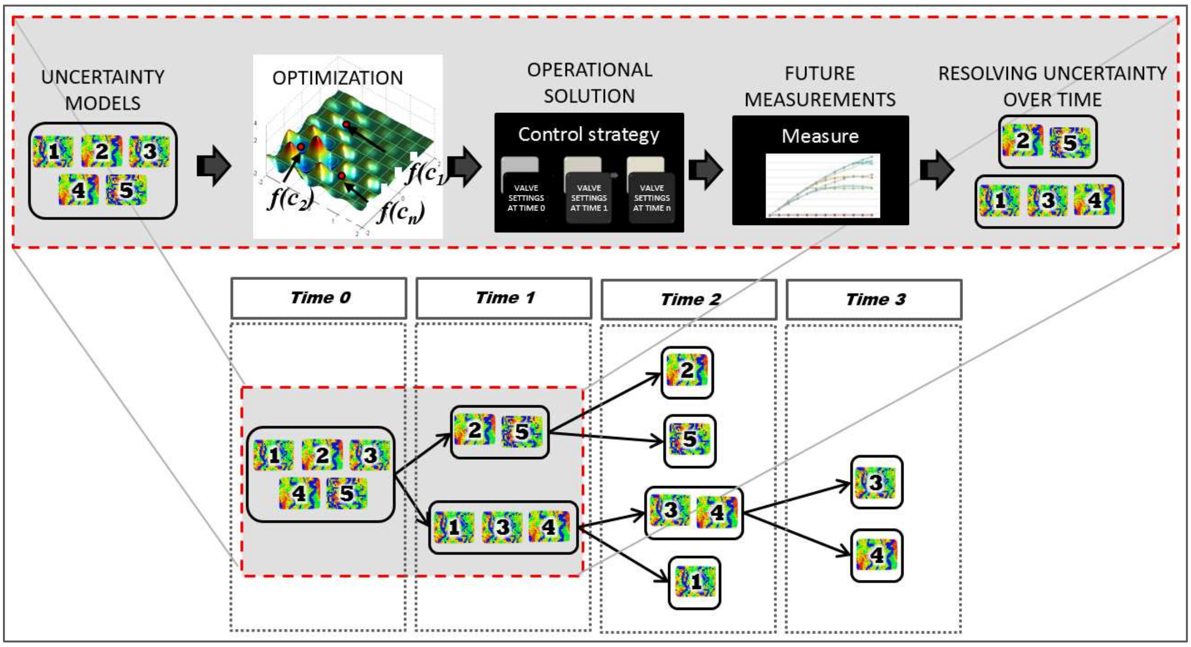

Figure 6 – FlexWell Optimization and Decision Workflow

We implemented this procedure, following the optimization routine proposed by Yeten et al. (2002), such that the performance of the reservoir for a particular set of valve settings can be determined via forward simulations. This is accomplished by dividing the entire simulation period into n optimization steps (these steps are distinct from the simulator time steps). The valve settings for the first period (time 0 to time 1) are then optimized. This optimization is performed such that the settings for this period will be the optimum for the entire simulation. We note that this strategy can be applied using different optimization algorithms, when we seek the valve settings that maximize the objective function.

TO BE COMPLETED

5. Conclusions

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6. References

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