Assisted Procedures for Definition of Production Strategy and Economic Evaluation Using Proxy Models

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Abstract

New techniques for reservoir development are essential for dealing with the complexities of geological models. In this sense, numerical simulation is the tool used to define the quality of a production strategy. However, the process to define variables such as well numbers, completion layer, open timeline and operational conditions demand several simulations due to the high time consumption and computational effort. Sub-optimal results can be obtained from manual processes. Automatic processes can mitigate this problem but the computational effort is increased as a result of the number of simulations generated in the process.

In order to minimize this problem, this paper proposes an assisted procedure for its automatic part using proxy models to accelerate the process. Furthermore, due to the reduced time to evaluate options, it allows a better evaluation of the solution space using better optimization techniques. Proxies have been used in important applications such as risk analysis and history matching but the use for definition of production strategy is not common.

The proposed methodology involves the following components: statistical methods, experimental planning to generate the response surface methodology for the generation of proxies and consistency checking.

The results show that it is possible to apply proxy models for this type of problem and they can identify the best production strategies, reducing the computational effort during the process. The suggested procedure is to use proxies in the automatic part of the assisted procedure used in the optimization process.

The main contribution of this work was the demonstration that proxy models can be used for the definition of production strategies, bringing an additional option to the decision analysis process linked with petroleum field development.

Introduction

The main activity in reservoir engineering is the planning of strategies and economic evaluation for the development and management of petroleum fields. The numerical simulation is useful in a definition of a production strategy during the appraisal and development phases, especially in offshore heavy oil fields due to the low economic return, limited flexibility and importance of reservoir modeling. The flexibility is limited because of the requirements to design the production facilities based on the low amount of information. The use of reservoir simulation has several constraints, such as: high number of blocks, variables and attributes which are time-consuming for the simulation and processes analysis, mainly in complex fields. Besides the high number of possibilities in a production strategy definition and the computational time linked with the numerical simulation, the process can be slow, forcing simplifications in the optimization process and consequently, decreasing the probability of finding better solution for the problem.

Proxy models can be used as an auxiliary tool to deal with some of these constraints. This technique can simplify models with lower confidence levels in some outputs and an alternative for the numerical simulator in several procedures that do not require a higher precision in the results and a reduced number of simulations. Proxy models have been used in reservoir engineering applications, including uncertainty modeling, sensitivity analysis, history matching (Peng and Gupta, 2003 and Risso, 2007), risk assessment (Risso et al. 2007), performance prediction, upscaling (Schiozer et al., 2008) and development optimization (Venkataraman, 2000).

In this study, proxy models have been used in an assisted procedure for production optimization, involving an integration of automatic and manual parts, for a definition of production strategies, bringing an additional option to the decision analysis process linked with petroleum field development. Figure 1 presents the general idea of proxy model application used in this study.
The number of simulations in a traditional process of production strategy definition is high and due to some limitations of manual procedures, sub-optimal results can be obtained. One possible solution for this problem is to use automatic algorithms to find the best alternatives in all of the solution space. On the other hand, they can be an exhaustive search, demanding a high number of simulations to test many possibilities, many of them far from the global optimum. Proxy models can cover all the solution space with a low computational effort. Instead of using many simulations in a traditional or automatic process, it applies a pre-determined number of simulations to generate the proxy models. In order to guarantee the quality of the solution, a consistency checking of the proxy models is made.

The main objective of this study is then to use proxies in the automatic part of the assisted procedure for developing and accelerating the process for the definition of production strategy and economic evaluation. The final process of the optimization (manual part) was not performed in this study because the focus of this work is to show that proxy models can be used in the optimization process (automatic part).

**Proxy Models**

Proxy models are based on the integration of statistical methods, such as experimental design theory and response surface methodology, which allows the definition of a production strategy and the economic evaluation. Experimental design technique can be applied to reduce the number of reservoir simulations in this process and therefore to screen a definition of a production strategy. The response surface methodology allows substituting the reservoir simulator by an analytical model (proxy model) in one part of the process.

The response surface methodology (RSM) can be generated by statistical design. It is a collection of mathematical and statistical techniques to model and analyze problems in which a response of interest is influenced by several variables (Montgomery, 1997). This RSM allows for substituting the reservoir simulator by a proxy model. It is necessary to correctly use the RSM as a proxy models to obtain good results (precision and reduction on computational effort), because this methodology involves statistical design and different possible proxies that can be obtained may significantly affect the results. This technique is already being applied with success in other processes linked to petroleum engineering such as risk analysis (Madeira, 2005), history matching of production (Risso and Schiozer, 2006). Thus, the use of proxy models in the definition of production strategy and economic evaluation can present good perspectives to increase the research in several reservoir challenges.

Box-Behnken designs were used in this study to generate the RSM. This design has several advantages. Compared with a three-level full-factorial design, a Box-Behnken design reduces the number of required experiments. This reduction becomes more significant as the number of factors increases. For five factors, a Box-Behnken design requires 41 experiments,
compared to 243 experiments required by a full three-level factorial, and 32 for a full two-level factorial. A class of three-level incomplete factorial designs for the estimation of the parameters in a second-order model was developed by Box and Behnken (1960). By definition, a three-level incomplete factorial design is a subset of the factorial combinations from the 3K factorial design.

The objective functions analyzed were Net Present Value (NPV), Cumulative Oil Production (Np) and Cumulative Water Production (Wp). In this study the parameters of the reservoir used were: three continuous (producer and injector well numbers, production capacity and injection capacity) and two discrete (production and injection completion layer and well open timeline). These variables are discretized in three levels (-1, 0 and 1).

**Methodology**

The methodology used to define the automatic part of the selection of a production strategy and the economic evaluation using proxy models combined three sequential steps as follows:

- **First step:** definition of an initial strategy definition;
- **Second step:** generation, validation and evaluation of proxy models to technical and economic parameters of a field;
- **Third step:** use of proxies in the automatic part of the assisted procedure used in the optimization process of production strategy definition.

**Initial strategy definition**

This stage consists of an initial pre-defined production strategy acting as a control. This model is defined as a synthetic case and constructed considering the available information on the Namorado Field.

**Generation, validation and evaluation of proxy models**

In this stage, the proxy models involve fundamental parts, as the proxy model definition (experimental design and RSM), complex parts in its validation and the part that the numerical simulator can be substituted by the proxies (analytical model). Proxy models are validated by consistency checking (comparing with reservoir simulation results).

**Application of proxy models in an assisted procedure in the optimization process**

The automatic part of the optimization process was completed using the statistical (experimental) design and the RSM. The generated proxies of the objective functions represented an automatic part of a production strategy in combination with the parameters and their levels. A simple optimization algorithm was used to define this part of production strategy for each proxy (objective function).

**Application**

**Model**

The synthetic model used in this study was constructed from the reservoir model of Namorado Field located in the Campos Basin with some modifications. The model has an area of 9.75 km² and an aquifer. The original volume of oil is 55 million m³. The numerical model of simulation has a Cartesian grid with 50 x 90 x 10 blocks with dimensions of 50 x 50 x 10 m. The reservoir outline is shown in Figure 2 and it can be seen the horizontal permeability distribution. The oil density is 27.72 °API and the fluid model used is the Black-Oil.
The initial production strategy was defined through a manually simplified strategy, consisting of 10 producer and 8 injector horizontal wells, in a uniform distribution that can be seen in Figure 3. The producers and the injectors were completed in the second and ninth completion layer, respectively; the production capacity is 11,000 m³/d and the injection capacity is 17,000 m³/d. All the wells are initially closed and they have an open timeline of 2 producers per injector every 40 days.
Some operational considerations for the wells:

- Maximum oil production of the producers: 2000 m³/d;
- Maximum water cut: 95% (producers were shut if this constraint had been violated);
- Maximum water injection of the injectors: 2200 m³/d;
- BHP target of the injectors: 340 Kgf/cm².

In the next stage, the most common critical parameters used in a production strategy definition were established (Table 1). Table 2 shows the discretization of each parameter in three levels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Producers and injectors wells numbers</td>
</tr>
<tr>
<td>A2</td>
<td>Producers and injectors completion layer</td>
</tr>
<tr>
<td>A3</td>
<td>Production capacity (m³/d)</td>
</tr>
<tr>
<td>A4</td>
<td>Injection capacity (m³/d)</td>
</tr>
<tr>
<td>A5</td>
<td>Wells open timeline</td>
</tr>
</tbody>
</table>

Table 2: Description of the discretized parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>8 Prod e 6 Inj = 14 Wells</td>
</tr>
<tr>
<td>A2</td>
<td>3 Prod e 8 Inj</td>
</tr>
<tr>
<td>A3</td>
<td>8000 m³/d</td>
</tr>
<tr>
<td>A4</td>
<td>13000 m³/d</td>
</tr>
<tr>
<td>A5</td>
<td>1 Prod e 1 Inj</td>
</tr>
</tbody>
</table>

The economic objective function, NPV, was calculated using the parameters showed in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil price</td>
<td>US$ 251.59 / m³ (US$ 40 / bbl)</td>
</tr>
<tr>
<td>Multiplication factor of produced oil type</td>
<td>0.70875</td>
</tr>
<tr>
<td>Oil production cost</td>
<td>US$ 10 / m³ or US$ 1.59 / bbl</td>
</tr>
<tr>
<td>Water production cost</td>
<td>US$ 1.57 / m³ or US$ 0.25 / bbl</td>
</tr>
<tr>
<td>Water injection cost</td>
<td>US$ 3.40 / m³ or US$ 0.54 / bbl</td>
</tr>
<tr>
<td>Abandon cost of the field</td>
<td>10 % of the initial investment</td>
</tr>
<tr>
<td>Platform (production capacity of 13000 m³/d)</td>
<td>300 Millions US$</td>
</tr>
<tr>
<td>Platform (production capacity of 17000 m³/d)</td>
<td>350 Millions US$</td>
</tr>
<tr>
<td>Platform (production capacity of 21000 m³/d)</td>
<td>400 Millions US$</td>
</tr>
<tr>
<td>Well cost (horizontal)</td>
<td>40 Millions US$</td>
</tr>
<tr>
<td>Discount rate</td>
<td>10 %</td>
</tr>
<tr>
<td>Royalties</td>
<td>10 %</td>
</tr>
<tr>
<td>PIS + COFINS</td>
<td>3.65%</td>
</tr>
<tr>
<td>Taxes</td>
<td>33%</td>
</tr>
</tbody>
</table>

Results

After the application of the experimental design, the proxy models for NPV, Np and Wp are presented in Equations 1, 2 and 3, respectively. Each combination of the parameters was considered as a production strategy, with the choice depending on the decisor, who will analyze the objectives and the strategies of the company.

1 Prod = Producer(s)
2 Inj = Injector(s)
3 CAPEX is the investment in the initial stage of a project. In this paper, CAPEX has two components: the platform cost that is variable; and the other investments that were fixed on US$ 150 million.
NPV (millions US$) = 280.9 − 97.7 · (A1) + 12.2 · (A1^2) + 24.9 · (A2) − 9.4 · (A2^2) − 19.4 · (A3) − 22.0 · (A3^2) + 13.4 · (A4) − 10.3 · (A4^2) − 22.8 · (A5) − 1.7 · (A5^2) + 2.6 · (A1) · (A2) + 5.8 · (A1) · (A3) + 7.5 · (A1) · (A4) − 10.3 · (A1) · (A5) + 1.9 · (A2) · (A3) − 2.3 · (A2) · (A4) + 14.1 · (A2) · (A5) + 10.6 · (A3) · (A4) − 4.6 · (A3) · (A5) + 0.5 · (A4) · (A5)

\[ \ldots \ldots (1) \]

Np (millions m³) = 25.926 + 0.885 · (A1) + 0.324 · (A1^2) + 0.435 · (A2) − 0.103 · (A2^2) + 0.121 · (A3) − 0.031 · (A3^2) + 0.200 · (A4) − 0.136 · (A4^2) − 0.151 · (A5) − 0.068 · (A5^2) − 0.058 · (A1) · (A2) − 0.002 · (A1) · (A3) + 0.097 · (A1) · (A4) − 0.101 · (A1) · (A5) + 0.011 · (A2) · (A3) − 0.046 · (A2) · (A4) + 0.347 · (A2) · (A5) + 0.033 · (A3) · (A4) − 0.008 · (A3) · (A5) + 0.015 · (A4) · (A5)

\[ \ldots \ldots (2) \]

Wp (millions m³) = 68.32 + 6.74 · (A1) − 4.03 · (A1^2) − 0.68 · (A2) + 0.77 · (A2^2) + 0.67 · (A3) − 0.60 · (A3^2) + 7.63 · (A4) − 5.17 · (A4^2) − 0.76 · (A5) + 0.68 · (A5^2) − 0.78 · (A1) · (A2) + 0.11 · (A1) · (A3) + 6.16 · (A1) · (A4) − 0.02 · (A1) · (A5) + 0.36 · (A2) · (A3) + 0.21 · (A2) · (A4) + 0.20 · (A2) · (A5) + 0.45 · (A3) · (A4) + 0.03 · (A3) · (A5) + 0.52 · (A4) · (A5)

\[ \ldots \ldots (3) \]

These proxies were validated and the results are not shown here because they are not the main objective of this study. In Figure 4 and Figure 5, it is possible to see all solution space of NPV vs Np and NPV vs Wp, respectively, where it is possible to find the maximum or the minimum for each. The stage before the initial optimization refers to combinations used in the proxy models generation. Furthermore, the proxies were generated and used in the optimization process; a search for possibilities of application was made, and finally, the best was chosen, considering the company objectives and strategies to be used in the automatic part of the assisted procedure in the optimization process. These results made the definition of the maximum of NPV and Np and the minimum of Wp possible, consequently becoming the initial step of the manual part of the assisted procedure of a production strategy definition.

In Figure 4, it is possible to see an empty region, not covered by proxies, because they have some number and range of parameters limitations to generate the proxies. This optimization is an initial step for the automatic process and can be developed to provide better solutions for the problem. Graphical analysis can give an idea of the following steps of an automatic process of selection of a production strategy. For example in the Figure 4, it can search for better results from the maximum NPV solution.

Figure 4: NPV vs Np along the combinations using proxies.
In Figure 5, the decisor can change the alternatives based on the generated solution space using the proxy models. For instance, a reduction can occur at approximately 11% in Wp with a reduction of 2% in NPV. This is a good example of how proxies can change the alternatives and can be used in an assisted procedure to define a production strategy, starting the optimization process (manual part of an assisted procedure).

![Proxy Model: NPV vs Wp](image)

**Figure 5:** NPV vs Wp along the combinations using proxies.

The values of each parameter and the objective function used in the optimization process during the automatic part of an assisted procedure can be seen in Table 4. After this automatic part, it would be possible to continue the optimization process (manual part) from these initial steps (it was not done in this study).

<table>
<thead>
<tr>
<th>Decision</th>
<th>Wells Number</th>
<th>Completion Layer</th>
<th>Capacity (m³/d)</th>
<th>Well open timeline</th>
<th>Objective function – Proxy models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Prod</td>
<td>Inj</td>
<td>NPV (US$)</td>
</tr>
<tr>
<td>MAXNPV</td>
<td>8 P e 6 I</td>
<td>1 P e 10 I</td>
<td>9200</td>
<td>16500</td>
<td>3 P e 1 I</td>
</tr>
<tr>
<td>MAX NP</td>
<td>12 P e 10 I</td>
<td>1 P e 10 I</td>
<td>14000</td>
<td>21000</td>
<td>3 P e 1 I</td>
</tr>
<tr>
<td>MIN WP</td>
<td>12 P e 10 I</td>
<td>1 P e 10 I</td>
<td>8000</td>
<td>13000</td>
<td>3 P e 1 I</td>
</tr>
</tbody>
</table>

Besides observing the proxies generation during the optimization in addition to their statistical validation, the cross validation between simulation and proxy model was necessary as well. The cross validation of NPV, Np and Wp can be seen in Figure 6, 7 and 8, respectively. In these figures, the proxies were adjusted in comparison with the simulation and can be a substitute for the simulator to generate the values of the objective function in the automatic part of the assisted procedure.

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4 MAX – Maximization of the parameter in analysis.
5 MIN – Minimization of the parameter in analysis.
Figure 6: Cross Validation of NPV.

Figure 7: Cross Validation of Np.

Figure 8: Cross Validation of Wp.

Conclusions

The use of proxy models can be a good alternative to an assisted procedure to define the production strategy and economic evaluation in petroleum fields. These models are able of efficiently substituting the reservoir simulator in an automatic part that demands many simulations, used as an initial part of a strategy production process, as well as employed as the solution in an initial strategy that would be further tested with the simulator (validation or consistency stage).

The main contribution of this work was to point out proxy models that can be used in the definition of production strategy, bringing an additional option to the decision analysis process linked with petroleum field development.

Nomenclature

API = American Petroleum Institute
BHP = Bottom hole pressure
EPi = Initial production strategy
NPV = Net Present Value
Np = Cumulative Oil Production
RSM = Response Surface Methodology
Wp = Cumulative Water Production

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