Use of Streamlines and Quality Map in the Optimization of Production Strategy of Mature Oil Fields
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Introduction
The definition of a production strategy of oil fields comprises several study phases. In the beginning of the field life the data are scarce, what reflects in a great uncertainty and in the one adoption of an initial production strategy, without great refinement of the solution. After the choice of the initial strategy, appears the necessity of refinement since the uncertainties diminish in function of the biggest amount of data, what reflects in the best detailing of the field model to be simulated. In the third phase occurs the optimization of production strategy of the developed or mature oil fields. In this stage, the reservoir knowledge increases, and more geological are available, reducing the involved uncertainties in the optimization process.

The strategy optimization is a complex procedure that demands the analysis of the producer and injector wells behavior to know which wells can be modified and the analysis of a great number of variable that influence the process, as for example, geological and fluids properties, production and pressure data. Developed and mature oil fields optimization presents minor flexibility because although the used models are more realistic, there are more restrictions of changes after the total or partial implementation of the initial strategy. Therefore with perforated wells and in operation, modifications must be made of different form to present economic viability. This complexity increases with the difficulty in to apply mathematical optimization methods in function of the great computational effort required in the modeling process. This difficulty becomes necessary the use of support tools as the streamline simulation and the quality map, that allow to define additional objective functions that classify the wells and determine which regions of the reservoir present mobile residual oil to be recovered.

The streamline simulation is used to study the fluid flow pattern in the field, determining the efficiency of injector wells and distribution of injection costs for producer wells. The quality map is used to define regions of the reservoir with mobile residual oil, defining regions for perforation and completion of producer wells.

The conventional simulation (based on finite difference) is used to do the main simulations to the tests that verify the use of the support tools. All the economic analysis is made based on conventional simulations output.
Supporting Tools
Mezzomo and Schiozer (2002) work with a methodology to support managers in the decision making process for water injection planning optimization for fields in development stage and under operational and economic restrictions. Nakajima and Schiozer (2003) [a] developed a methodology to support reservoir managers to optimize a strategy developed with horizontal wells. It does not provide unique solutions, since this optimization problem depends on many factors which may lead to a set of alternatives. His methodology is based on economic optimization and the main objective is to maximize the net present value of the field.

In developed and mature oil fields studies is necessary a detailed analysis of field behavior, because the geological and numerical models are more precise, and production history data permits improve the reservoir characterization. The streamline simulation and quality map assist this analysis, determining parameters that through the use of conventional simulation are more difficult to determine.

Streamline Simulation. The streamline simulation currently is accepted as an effective and complementary tool for reservoir modeling. This tool allows working models that possess a raised number of blocks, with more complex and heterogeneous geology. Thiele (2001) shows that the streamline simulation functions with six key ideas: 1) Tracing streamlines in three dimensions using time-of-flight; 2) Recasting the mass conservation equations in terms of time-of-flight; 3) Periodic updating of streamlines; 4) Numerical solutions along streamlines; 5) Including gravity presented a problem; 6) Use in compressible flow.

Batycky et al. (1997) illustrate the application of streamline simulation method to a real field data set, the House Mountain waterflood in central Alberta, Canada. The streamline simulation accurately models overall field historical data and on a well-by-well basis accurately models performance in 60% of the wells. The authors had concluded that streamline method is applicable to three-dimensional field scale waterflood simulations with only minor approximations to data input and can either include larger simulation areas with more wells and/or reduce the need for substantial upscaling.

Grinestaff (1999) demonstrate the use streamlines simulation to waterflood management. Your focuses in three areas: 1) how the streamline models require a different approach to simulation; 2) using streamlines to find inefficiencies in the waterflood and set injection targets; 3) the benefits of a history matched model. The main conclusions of the author had been: streamline simulation provides a rapid means to quantify injector to producer relationships and other fluid displacement in complex waterfloods; streamline models should not be developed with conventional simulation model building and history matching techniques; production data should be the primary source of information used to history match a developed waterflood area.

Maschio and Schiozer (2002) analyzed the performance of streamline simulation comparing the results for this tool with finite differences. It was shown that streamline simulation is very efficient, in terms of run time and accuracy, for incompressible or slightly compressible models, with high degree of heterogeneities and large grid size, which represent a limitation for conventional finite difference simulators. For these cases streamline simulation have clear advantages compared to conventional simulators. Once streamline simulation must necessarily neglect or simplify some important physics in order to run quickly, it should not be intended to match or rigorously predict field recovery when complex physics related to fluids properties and fluids flow must be considered. The main limitation is when highly compressible fluids are present in the model. In these cases, conventional simulation is required for more rigorous and reliable evaluations.

This work applies the streamline simulation in a field in production phase (developed or mature), where the main objective is to study the flow distribution between producer and injector wells.

Quality Map. Cruz et al. (1999) introduce the concept of a quality map, which is a two-dimensional representation of the reservoir responses and their uncertainties. The quality concept may be applied to compare reservoirs, to rank stochastic realizations and to incorporate reservoir characterization uncertainty into decision making, such as choosing well locations, with fewer full field simulation runs. The authors used a very large case study using fifty different realistic reservoirs to demonstrate the following uses of the quality maps: 1) well location for a specific realization using the quality map of that realization; 2) well location in a manner that is robust with respect to the uncertainty and reducing the number of scenarios in the “full approach”, using the lower quartile quality map; 3) reduction of the number of realizations in the “full approach” to just one, by identifying a representative realization for each scenario, 4) ranking of realizations for several purposes using the quality map of all realizations; 5) reservoir comparisons using the average values of the mean quality and uncertainty quality maps. The main conclusions of the author had been: the quality map permits a simple two-dimensional visualization of how good the area is for production values and of the uncertainty in those values; the quality map along with a simple optimization algorithm may be used to determine good locations for vertical producer wells; the lower quartile quality map allows the incorporation of geological uncertainty into reservoir management decision making; one representative realization can be identified for each production scenario using the quality maps, allowing scenario comparisons with similar results to the ones using the expected value over all realizations but with much less CPU time expense.

Nakajima and Schiozer (2003) [b] propose the use of a quality map to guide reservoir managers in horizontal wells placement. This map represents the regions with production potential in a reservoir, providing the best place to locate a well. Three methods of quality map construction are used: (1) numerical simulation, (2) analytical and (3) fuzzy system. These three methods were developed to provide a fast evaluation in order to reduce time-consuming and computational efforts. The main conclusions the Nakajima and Schiozer (2003) had been: the use of quality map help the decision-making process in petroleum field management; the quality maps can be applied in any stage of reservoir life,
reducing time-consuming and computational efforts in the production strategy optimization process; the analytical method and fuzzy system method were considered more flexible, since it is easier to use.

This paper study the application of the quality map constructed through numerical simulation to an oil field in production phase (developed or mature), identifying regions of the reservoir with residual oil localization.

Methodology
Guimarães (2005) developed a methodology for optimization of fields in production phase, where the objective-functions NPV, Np, W, G, Qo_m and Mp are used for to determine the efficiency of producer well. The methodology used the streamline simulation and quality map as auxiliary tool in the optimization process of fields in production phase. This paper focuses on the feasibility and application of streamline simulation and quality map in the optimization process, showing the main procedures to use the techniques

Streamline Simulation Analysis. Two tests are made to study the application of streamline simulation:

Test one - efficiency of injector well (Ef): Ef is defined as being the produced oil volume ($V_{op}$) divided by the injected water volume ($V_{iw}$) responsible for the production of this oil (Equation 1).

$$Ef = \frac{V_{op}}{V_{iw}}$$

(1)

To verify the application of the Ef, all the injector wells must have individually tested shut down. The relation between the variation of the field NPV and the Ef must be investigated through graphs that present correlation studies between the analyzed functions. The NPF for the field is calculated through conventional simulation.

Test two - distribution of injection costs for producer wells: Guimarães (2005) uses revenue and cost curves to determine of producer wells closing date. These curves are constructed using production data for the behavior forecast period and revenue (oil sale) and cost (water and oil production) data. The relation between producer and injector wells is gotten through the streamline simulation, where the injected water volume directed to a producer well has its costs added to the production costs of the well that receives this water. The revenue and cost curves for the well are calculated through conventional simulation.

Quality Map Analysis. The quality map is constructed by running a flow simulator multiple times and varying the position of a single well in each run to cover the entire horizontal grid. Each run evaluates the quality for the horizontal cell where the well is located. The quality unit is the NPV a certain time of production. In the simulations, the well is completed in all oil layers with automatic shut down of the layer when some water cut limit is reached. No rate limits are imposed, allowing the well to produce the maximum it can. Only a minimum bottom hole pressure and a minimum oil rate must be specified in accordance with the real operational limitations of the well.

Three methods to generate numerical quality map are tested with the objective to define which of them must be used in studies of developed or mature fields. These methods are: 1) single well tested in all the cells of the horizontal grid (accurate map); 2) single well tested in a mesh of tests with 59 points present in the horizontal grid (intermediate map); 3) 59 points present in the horizontal grid simulated at the same time (less accurate map). These three maps must be constructed for the end of the production history period (Initial Quality Map) and for the end of the forecasting period (Final Quality Map). The validation of these maps is made through tests where ten horizontal wells perforated in diverse regions of the reservoir. Plots of NPV versus quality index indicate the correlation between them.

In order to test quality maps for injector wells, eight wells were perforated in several regions of the reservoir.

Application
The study presented in this paper was applied to an offshore field. The STOIP of the field is approximately 100 MMm$^3$. It is a developed field, with 1800 days of production history. This field has useful life of 2922 days (keeping the production strategy applied during the history period). The field is drained by 11 oil producer wells and 9 water injector wells. In 1800 days, all the producer and injector wells already are in operation. The water injection began after 180 days of primary production.

The simulation model is composed of a grid of 60 blocks in the x direction, 35 blocks in the y direction and 7 layers (60x35x7), discretized into a Cartesian grid. Datum depth is located at 3000 m, water oil contact is located at 3100 m and gas oil contact is located at 2900 m. In Fig. 1 is presented a three-dimensional horizontal permeability map of the reservoir.

Results and Discussion
Initially, each tool was analyzed separately to evaluate its potential and to define procedures to integrate them in the optimization process.

Streamline Simulation. In this section are presented the results of the application of the streamline simulation.

Test one: Table 1 presents the obtained results for the injector wells shut down in 1800 days. The shut down of injector wells with low efficiency (Ef) provides high NPV increasing. On the other hand, when injectors with high efficiency are shut, a high decrease in NPV is observed. Fig. 2 shows good linear correlation between NPV and Ef (dashed line in the Fig. 2).

Test two: Revenue and cost curves were constructed for all producer wells present in the field, but only the results for the wells PH-02 e PH-14 will be presented. Fig. 3 and the Fig. 4 show, respectively, the revenue (blue) and cost (red) curves for the PH-02 and PH-14. The green curve is the additional cost related to the injector costs distributed to the producers.
For the PH-02 (Fig. 3), the red curve crosses the blue curve in 2895 days and the green curve in 2779 days. The difference between the crossing points is about 100 days. For PH-14 this difference is approximately 300 days. This can influences the estimation of the well shut down date.

**Quality Map.** In this section are presented the results from the quality map analysis, perforating new producer and injector horizontal wells.

**Quality map analysis.** Fig. 5 shows the accurate map generated for 1800 days. For the construction of this map were necessary 853 simulations. Fig. 6 and Fig. 7 present, respectively, the intermediate map and the less accurate map. The intermediate map required 59 simulations, and the less accurate map required 1 simulation. The accurate map (Fig. 5) shows larger concentration of regions with high unity quality. Figs. 8, 9 and 10 show, respectively, the accurate map, the intermediate map and the less accurate map for 2922 days. This map also presents larger concentration of regions with high unity quality. The difference between the maps constructed for 1800 days and 2922 days is the size of the regions that present high unit quality, what can be explained by the smaller oil volume in the field in 2922 days.

**Perforation of producer wells.** For testing and validation of all constructed quality maps, 10 horizontal wells were perforated one at a time in several regions of the reservoir. Each new well corresponded to an individual model, in order to evaluate the individual contribution of each well. Figs. 11, 12 and 13 show field NPV increase versus quality index, for the accurate map, the intermediate map and the less accurate map for 1800 days, respectively. Figs. 14, 15 and 16 show the same for 2922 days. Linear correlation is indicated in all plots by dashed lines.

The accurate maps generated for 1800 and 2922 days present the best linear correlations, but its construction needed 853 simulations. The less accurate maps were generated with 1 simulation, but they show worse correlations. The choice of the construction method of quality maps depends on the objective. In the case of the user to need more precision, the accurate map can be desirable. Intermediate and less accurate maps can be used when computational and time resources are limited.

**Perforation of injector wells.** Eight injector wells were also perforated one at a time. Table 2 shows the NPV generated with the perforation of these wells. Fig. 17 and Fig. 18 present, respectively, its locations in the poor quality region for map constructed for 1800 and 2922 days. The wells represented by yellow symbols provided better results. They are predominately located in the neighborhood of the high quality area in the map generated for 2922 days.

**Optimization process.** In order to evaluate the benefits of the support tools, two optimization processes are presented: the first one without using the tools (optimization 1) and the second using them (optimization 2). In Fig. 19 is presented the evolution of the optimization process without the use of the support tools. In the y-axis is the percent variation (with respect to the initial model) of the NPV, Np, Wp, Wi and Gp and in the x-axis is the number of runs in the optimization process. Fig. 20 shows similar plot for optimization 2. The comparison of the results from the two optimization processes shows following benefits related to optimization 2: (1) decreasing the effort in terms of time consuming for the manage the process and in terms of number of iterations (optimization runs), for optimization 1 was necessary 50 iterations, while optimization 2 required 39; (2) increasing 79 % in NPV against 73 % from optimization 1; (3) small increasing in water injection (Wi), approximately 2 %, while in the optimization 1 the water injection increase 17 %; (4) decreasing 55 % in water production (Wp) against 37 % for optimization 1. Although increasing Np was smaller in optimization 2, a better water management allowed improving NPV.

**Conclusions**

This paper presented the application of streamline simulation and quality maps for optimization of production strategy that can be used for mature and developed field. These support tools permitted to reduce the total computational and time effort, allowing the improvement of the optimization process. Some particular points can be emphasized:

1. The application of the Ef function determined through streamline simulation presented good results for analysis of injector wells.
2. Distribution of injection costs can be generated using streamline simulation and applied to producer wells analysis.
3. The accurate map presents the best correlation between quality index and NPV increase. However, more computation effort was necessary. The use of more or less accurate maps depends on the compromise between time and computational resources and the desirable precision.
4. Final quality maps showed better results for producer and injector wells allocation.

**Nomenclature**

- Ef = efficiency of injector well
- G = function related to gas production
- IHT = injector well for test
- IHW = injector well
- Np = cumulative oil production
- NPV = net present value
- PH = producer well
- Qo_m = average oil flow rate
- Vop = produced oil volume
- Viw = injected oil volume
- W = function related to water production
- Wi = cumulative water injection
- Wp = cumulative oil production

**References**


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Table 1 – Injector well shut down in 1800 days.

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<th>Wells</th>
<th>NPV (millions US$)</th>
<th>Ef</th>
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<tr>
<td>Initial strategy</td>
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<td>-</td>
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<tr>
<td>IHW-01</td>
<td>107,1</td>
<td>0,610</td>
</tr>
<tr>
<td>IHW-02</td>
<td>112,6</td>
<td>0,602</td>
</tr>
<tr>
<td>IHW-03</td>
<td>103,6</td>
<td>0,626</td>
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<tr>
<td>IHW-12</td>
<td>106,7</td>
<td>0,753</td>
</tr>
</tbody>
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Figure 1 – Three-dimensional horizontal permeability map.

Figure 2 – Linear correlation between NPV and Ef.

Figure 3 – Revenue and cost curves for the PH-02.

Figure 4 – Revenue and cost curves for the PH-14.
Figure 5 – Accurate map generated for 1800 days.

Figure 6 – Intermediate map generated for 1800 days.

Figure 7 – Less accurate map generated for 1800 days.

Figure 8 – Accurate map generated for 2922 days.

Figure 9 – Intermediate map generated for 2922 days.

Figure 10 – Less accurate map generated for 2922 days.
Figure 11 – NPV x Unit Quality for accurate map generated in 1800 days.

Figure 12 – NPV x Unit Quality for intermediate map generated in 1800 days.

Figure 13 – NPV x Unit Quality for less accurate map generated for 1800 days.

Figure 14 – NPV x Unit Quality for accurate map generated in 2922 days.

Figure 15 – NPV x Unit Quality for intermediate map generated in 2922 days.

Figure 16 – NPV x Unit Quality for less accurate map generated in 2922 days.
Table 2 – NPV resulting of perforation of injector wells.

<table>
<thead>
<tr>
<th>Wells</th>
<th>NPV (millions US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial strategy</td>
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</tr>
<tr>
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<tr>
<td>IHT-08</td>
<td>126.6</td>
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</table>

Figure 17 – Injector well locations in less accurate map generated in 1800 days.

Figure 18 – Injector well locations in less accurate map generated in 2922 days.

Figure 19 – Evolution of the optimization process without the use of the support tools.

Figure 20 – Evolution of the optimization process with the use of the support tools.