Well Site Selection Algorithm Considering Geologic, Engineering and Economic Constraints:
A Progress Report

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Abstract

Well placement decisions must be made in the face of many geological, engineering and economical constraints. Some of these goals include (1) maximum intersection of connected regions of high quality reservoir, (2) avoidance of fluid contacts that could cause early breakthrough and reduced productivity, (3) compliance with physical drilling constraints such as curvature and maximum distance, and (3) placement in proximity to platform locations. We consider well placement subject to such complex constraints and accounting for geological uncertainty quantified by multiple geostatistical realizations.

An iterative algorithm is proposed for well placement subject to multiple constraints and “optimality” relative to uncertainty in the reservoir model. Preliminary results were presented in CCG Report One (1999). Incremental results are presented this year due to coursework.

Introduction

Placement of wells is an important problem that depends to a large extent on reservoir geometry and continuity. Since the reservoir is never known exactly, geostatistical realizations are being increasingly used to represent reservoir heterogeneity and uncertainty. There have been a number of attempts to use geostatistical models for well placement.

In 1995, Goggin et al. (1) reported a well-position optimization method based on statistics. Well planning using a deterministic 3D model or an inverted seismic data volume during the drilling of a horizontal well has been performed in a number of places, see for example Badgett et al. (2). Gutteridge et al.(3) takes the application of 3D geological reservoir models forward from basic well planning, to a screening and ranking of multiple well path options based on quality of connection to volumes of net sand and on instantaneous productivity index. Quality factor maps are used in their research as potential well positions, and then well paths are ranked in the order to obtain optimal well sites. They takes advantages of what they called ‘shared earth model’, the model generated by latest 3D modeling packages.

Also in 1996, D. Seifert (5) generated geological 3-D stochastic reservoir models by integrating reservoir specific and outcrop analogue data into a hybrid deterministic-stochastic model. The model provides the basis for determination of the optimum well trajectories and subsequent risking of their success. In his work, both horizontal wells and inclined wells are evaluated over multiple realizations.
“Integer Programming Optimization” was also applied as an automatic well selection method by S. Vasantharajan et al. (4). In his work, quality map is used as input to the well site selection.

No previous work considers the many restrictions on well placement. In this paper, an integrated optimization algorithm is presented to take care of the parameters encountered both in exploration and development stage, such as the geo-objects a well trajectory may intersect, connected volume, various lithologic properties of reservoir rock like porosity, permeability and geologic structure and structural position. Also, well path sinuosity is captured by curvature of the well path.

We propose an iterative algorithm that can simultaneously consider multiple constraints in component objective functions. They must be combined into a single objective function to be minimized. The weighting of the different components will consider the work of Deutsch (6). We present progress to date.

**Grid Topology**

A 3-D reservoir model can be represented by an areal grid with \( nx \) cells along \( x \) direction and \( ny \) cells in the \( y \) direction. The cell size is \( dx \) and \( dy \) in the \( x \) and \( y \) directions, respectively. We consider a constant \( dx \) and \( dy \), but this could easily be relaxed. In order to account for the depth of the reservoir, we employ a variable depth array \( D(i,j), i = 1...nx, j = 1...ny \), see Figures 1 and 2.

**Well Path definition**

A well path is a 1-D trajectory defined by a sequential set of \( N \) coordinate locations \( \{(x_i,y_i,z_i), i = 1,...N\} \), e.g., see Figure 3. The trajectory between the \( N \) control points may be taken as linear or following a spline curve. The control points could be vertical, inclined, or almost horizontal, see Figure 4.

**Geo-object (Flow Unit) Calculation**

A reservoir consists of connected regions, which we wish to produce with the fewest number of wells in the best locations. The different connected regions in a reservoir are called “geo-objects” or flow units. Each geo-object is a collection of net (reservoir quality) cells that are connected together but disconnected from other geo-objects. Figure 5 illustrates three geo-objects, while the outside cells are non-reservoir quality. Geo-objects are normally sorted according to their sizes, where geo-object 1 is the largest, 2 is the second largest and so on. Details on calculation of geo-object connectivity can be found in Deutsch (4). The program for geo-object calculation has been integrated into the well selection program.

**Connected Volume to Well Locations**

The connected volume (CV) to a well location represents the reservoir volume that can be drained by a well, that is, the reservoir volume that is reservoir quality and connected to the
$D_x$ $D_y$ $N_x =$ number of cells along $X$ (14) this case

$N_y =$ number of cells along $Y$ (32) this case

Figure 1: Plan view of grid system.

$D_z(1,1,5)$

Figure 2: Definition of $D_z$s.
Figure 3: Definition of a well path with 4 control points.

Figure 4: Three well types: horizontal, vertical and deviated wells
Figure 5: Schematic illustration of geo-objects and connected volume to a well location. The dashed lines represent the drainage radius.

well location and within the drainage radius of the well. The connected volume depends on the geo-objects intersected by the well and their distribution within the drainage radius. In presence of multiple geostatistical realizations, the average or expected value of the connected volume for a well location may be determined.

Let $\Omega$ represent the set of all cells within the drainage radius of the well. The indicator variable $i(u, u_w)$ represents the probability of a location $u$ being connected to the well location, that is,

$$i(u, u_w) = \begin{cases} 
1, & \text{if location } u \text{ is connected to well at location } u_w, \\
& \text{and } u \text{ not connected to another well} \\
0, & \text{otherwise}
\end{cases} \quad (1)$$

The connected volume for well $u_w$ is the indicator-weighted sum of all cells in the drainage radius,

$$CV_w = V_c \sum_{u \in \Omega} i(u; u_w), \text{ where } V_c \text{ is volume of a cell} \quad (2)$$

Note that we could easily multiply this term by the porosity of each cell to get a true pore volume. A single well can intersect several geo-objects simultaneously. The connected volume is the sum of all the cell volume that fit the criteria specified above.

For multiple well configurations, we need to calculate the total $CV$ of all the wells, the cumulative connected volume (CCV). It can be expressed in the form of object function...
component:
\[ O_{CV} = \sum_{w=1}^{n_w} CV_w = V_c \sum_{i=1}^{n_w} \sum_{u \in \Omega} i(u; u_w), n_w \text{ is number of wells} \] (3)

In combination with other objective components, \( O_{CV} \) can be used as a criteria for well positioning. For the same number of wells, we would prefer the well configuration with the greatest \( O_{CV} \).

The simplest case is when only one well location must be chosen. The \( O_{CV} \) for all candidate locations and possible well trajectories can be calculated and, then, the well trajectory is set to the one with the maximum connected volume. This procedure could be repeated sequentially to place multiple wells; however, this will not in general, achieve the maximum \( O_{CV} \). The number of combinations to consider is very large, which makes the multiple-well case difficult.

Geologic Structures and Structural Position

Geologic structure influences oil and gas accumulation and drainage in many ways and must be taken into account. The location of the fluid contacts relative to well locations is important.

The facies, porosity, and permeability vary widely and must be given careful consideration in any study of well placement. Production rates are higher in highly porous reservoir rocks. Permeability is critical, for if the resistance to flow is high, the rate of recovery will be slow. Wells in “tight” formations may quickly reach an uneconomic rate of production.

Sinuosity

Curvature \( \xi \) is defined as the change in angle of the tangent divided by the change in arc length:
\[ \xi = \lim_{M \to N} \frac{\Delta t}{s_{MN}} = \left| \frac{dt}{ds} \right| = |t'| \] (4)
\( \Delta t \) is the change in angle of the two successive tangents \( t \) and \( \Delta t \) on a space curve. \( ds \) is the change of the arc length from point \((x_N, y_N, z_N)\) to \((x_{N+1}, y_{N+1}, z_{N+1})\). The parametric formula to \( t \) can be described as follows,
\[ \xi = \sqrt{x''^2 + y''^2 + z''^2} \text{ (parametric parameter)} \] (5)
where, \( x'' = d^2x/ds^2 \) \( y'' = d^2y/ds^2 \) \( z'' = d^2z/ds^2 \)

The above equations are defined in the continuous domain, discretized versions of the partial derivatives must be found before implementation is possible. Using the forward and backward definitions of the derivative, the following difference functions can be used in place of the partial derivatives:
\[ X' \approx \frac{X_{N+1} - X_{N-1}}{2\Delta s} \]
\[ Y' \approx \frac{Y_{N+1} - Y_{N-1}}{2\Delta s} \]
Figure 6: Definition of curvature
\[
Z' \approx \frac{Z_{N+1} - Z_{N-1}}{2\Delta s}, \quad X'' \approx \frac{X_{N+1} - X_N - X_{N-1}}{\Delta s^2}, \quad Y'' \approx \frac{Y_{N+1} - Y_N - Y_{N-1}}{\Delta s^2}, \quad Z'' \approx \frac{Z_{N+1} - Z_N - Z_{N-1}}{\Delta s^2}
\]

The units for curvature is degree/length units, where the magnitude depends on the length quantity.

**Fluid contacts**

The closeness of the well to the oil water contact may be penalized by \(O_{WC} = m_1 - l_{wc}\), where \(l_{wc} = \sqrt{(x_w - x_c)^2 + (y_w - y_c)^2 + (z_w - z_c)^2}\), \(w\) is the closest point on the well path to the fluid contact plane, \(c\) is the fluid contact plane, and \(m_1\) is a constant associated with distance from well trajectory to fluid contact. Gas oil contact restriction could be defined similarly.

**Platforms / Drilling Pads**

Sometimes the well sites are restricted to be drilled from central locations such as platforms or drilling pads. The optimization program should have the ability to account for this constraint.

**Objective Function**

All objective function components are combined. The method introduced by Deutsch (5) is used to combine the effects of different restrictions. The final objective function \(O\) is made up of the weighted sum of \(C\) components: \(O = \sum_{i=1}^{C} w_i O_i\) where \(w_i\) and \(O_i\) are the weights and components objective functions.

Notice that each component objective function \(O_C\) could be expressed in widely different units of measurement. Equal weighting causes the component with the largest magnitude to dominate the global objective function. All decisions of whether to accept or reject a perturbation are based on the change to the objective function,

\[
\Delta O = O_{new} - O_{old}
\]

with

\[
\Delta O = \sum_{c=1}^{C} w_c (O_{cnew} - O_{cold}) = \sum_{c=1}^{C} w_c \Delta O_c
\]

To make each component contribute equally to the change in the objective function \(\Delta O\), weights \(w_c, c = 1, \ldots, C\). This is to say, each weight \(w_c\) is made inversely proportional to the average change in absolute value of its component function:

\[
W_c = \frac{1}{|\Delta O_c|}, c = 1, \ldots, C
\]
Finally, the overall objective function is finally written as,

\[ O = \frac{1}{O^{(0)}} \sum_{c=1}^{c} w_c O_c \]

The initial value \( O^{(0)} \) is introduced to make sure the object function starts at 1.0 and a dimensionless annealing schedule may be used.

**Methodology**

Features of our problem formulation:

1. Choose number of wells to be optimized, note that wells can be combinations of deviated wells and horizontal wells etc.
2. Select initial locations and well path categories. Well path categories are horizontal, deviated and vertical wells. Clustering wells are handled by selecting initial location within one preset drilling spot.
3. Object function: Our objective here is a combination maximum of the following objective functions:
   - Maximize connected volume \( O_{cv} \)
   - Minimize penalty associated with closeness to fluid contacts \( \sum_{i=1}^{n} O_{fc_i} \), where \( n \) is the number of
   - Minimize penalty associated with interactive between wells \( O_{dp} \).
   - Other user defined restrictions and objectives.
4. The initial \( O_{all} \) is calculated;
5. Perturbation Mechanism: randomly choose a well and modify the well trajectory by randomly choosing the following options:
   - Collar translate: defined as randomly select a distance for the well path \((\Delta x, \Delta y)\) within preset scope and shift the whole well trajectory.
   - rotate: randomly choose a control point in the trajectory and randomly choose an angle with degree \((\Delta \alpha, \Delta \beta, \Delta \gamma)\) and rotate the trajectory.
   - change path: randomly choose a control point on the trajectory and randomly choose a shifting distance donated by \((\Delta x, \Delta y, \Delta z)\). Note: all the shifting distance and angles are restricted by curvature preset in advance.
6. Recalculate the overall objective function of the new configuration;
7. Decision rule: the whole procedure will continue once the objective function isn’t changing much

where \( O_{all\_cur} \) is the current value of objective function, \( O_{all\_pre} \) is the value it previous accepted and \( O_{tol} \) is the tolerance of objective function we set in advance.
Flow chart

A flow chart based on the above methodology is stated below.

References


Choose well path types and number wells

Randomly generate well trajectories with given curvature.

Randomly choose a well

Randomly choose one from below

Collar translate  Randomly rotate  Change path

Recalculate objective functions

$|O_{\text{curr}} - O_{\text{pre}}| < O_{\text{tol}}$?  Cycling given times?

End

Figure 7: Flow chart for optimization algorithm