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Optimal producer well placement and production planning in an oil reservoir

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ABSTRACT

Most of the available literature on optimal well placement has employed numerical simulators in a black box manner linked to an external search engine. In this work, we formulate the contents of that box inside a mixed integer nonlinear programming model for optimal well placement. We provide a unified model that integrates the subsurface, wells, and surface levels of an upstream production project. It links the production plan with the aforementioned elements, and economics and market. This results in a complex spatiotemporal mixed integer nonlinear model, for whose solution we modify and augment an existing outer approximation algorithm. The model solution provides the optimal number of new producers, their locations, and optimal production plan over a given planning horizon. To our knowledge, this is the first contribution that uses mathematical programming in a real dynamic sense by honoring the constituent partial differential equations.

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1. Introduction

The continuous depletion of oil reserves and rise in global oil demand have created a challenge for the oil exploration and production (E&P) industry. In 2011, the global oil production and demand were 88.4 mb/d and 88.2 mb/d respectively (OPEC, 2011b). OPEC estimates the demand to be 109.7 mb/d in 2035 (OPEC, 2011b). To meet this demand, the oil companies are expanding (OPEC, 2011a) their drilling activities (see Fig. 1). However, drilling oil wells is highly expensive and uncertain, and involves potential environmental hazards and economic risks. For instance, a vertical onshore (offshore) well can cost *MM*\$2–5 (*MM*\$8.3) on an average and a horizontal one can cost *MM*\$2.6–6.5 (*MM*\$10.2). Even after such expense, there is no guarantee that a well will be productive. In 2010, 56 of 227 exploration wells and 5 of 726 development wells of Shell Company (SHELL, 2010) turned out to be dry holes. BP's recent drilling blowout and resulting oil spill in the Gulf of Mexico keeps attracting news even now and BP has so far spent (BP, 2012) more than *B*\$8 in compensation. With such high financial and environmental stakes and significant uncertainty, there exist clear incentive and much recent interest to increase the overall economic efficiency and success rate of the hydrocarbon recovery processes by using systematic optimization approaches to obtain the best drilling and production scenarios.

In practice, the industry uses a variety of data, tools, and heuristics to select well locations. Typically, the entire task involves two stages. In the first stage, the engineering team defines a variety of development scenarios. In the second, it evaluates those scenarios via extensive simulations and develops various field production/injection profiles. Although intuitive and useful, such a sequential procedure is inherently empirical, ad hoc, and myopic, and has shortcomings. Much scope and benefits exist for the application of advanced optimization methods. A systematic model-based approach that simultaneously considers the drilling decisions along with the production/injection profiles over the planning horizon can yield significant returns in terms of economics, success, and recovery.

An integrated strategy for optimal well placement would encompass at least five elements in one single optimization model: (a) subsurface physics, (b) well geometry and dynamics, (c) surface facilities, (d) production/injection profiles, and (e) market and economics. Formulating and solving such an optimization model is a tremendous challenge. First, the myriad of decisions such as potential well locations, types, functionalities (producer/injector) (Yeten, Durlofsky, & Aziz, 2003), trajectories and inclinations (Ayodele, 2004), drilling schedules (Beckner & Song, 1995), and flow distributions (Isebor, 2009; Shafiee, Karim Aghaee, & Ayatollahi, 2010; Zerafat, Ayatollahi, & Rosta, 2009) make this a highly combinatorial optimization problem. Second, the physics of multi-phase

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Nomenclature

Sets and subscripts
AW active wells
IX interior grids with $i < I$
IY interior grids with $j < J$
IW grids with old injector
PW grids with old producer
f fluid (oil, water) index
n grids, location index
r iteration index
t time period index $(1,2,\ldots,T)$
τ time interval index $(1, 2, 3, \ldots, \sum_t \mathcal{T}_t)$
$x-, y-$ backward upstream weighting index
$x+, y+$ forward upstream weighting index

Parameters
A accumulation function
A_x, A_y directional cross-sectional area
a, b exponent terms – Corey's correlation
BHP bottom hole pressure
B_f formation volume factor of f
bf inverse of B_f
c_d drilling cost for one well
c_{iw} water injection cost per bbl
c_o oil selling profit per oil bbl
c_{pw} water production cost per bbl
c_v water viscosibility
c_w water compressibility
D demand
DC total drilling cost
g gravity acceleration
h^t time
H production horizon
I, J number of grid blocks (x, y)
IE^t injection capacity expansion
IIC initial injection capacity
IPC initial production capacity
$\boldsymbol{K}$ absolute permeability
k_r relative permeability
kr_0^o, kr_0^w end point relative permeability
L well length
P_c capillary pressure
P_r reference pressure
PE^t production capacity expansion
S_{or}, S_{wr} residual oil and water saturations
T number of time periods
$\mathcal{T}_t$ number of time intervals in period t
T^x, T^y directional transmissibility
THP tubing head pressure
TIC total injection capacity
$TLPC$ total liquid production capacity
TWP total water production
V volume of grid
WC water-cut ratio limit
α regression parameters
δ a very small number
β economic parameter in NPV definition
$u_r, \boldsymbol{w}_r, \omega_r$, penalty parameters
$\mu_{Bo,1}, \mu_{Bo,2}$ regression coefficients for $(\mu_o \times Bo)$
$\mu_r^0, \boldsymbol{\lambda}_r, \boldsymbol{\mu}_r$ Lagrange multiplier
$\mu_{o,1}, \mu_{o,2}$ regression coefficients for oil viscosity
ρ density
γ regression coefficient for well equations
Ψ connection transmissibility factor for wells

Variables
$d_{f,1}, d_{f,2}$ terms in accumulation
F net convective flow from each grid
M_f mobility of phase f
P pressure
q total production/injection
q_f oil/water production
$\mathbf{R}$ intermediate free variable for IPR equation
S water saturation
TLP^t Total liquid production in period t
TOP^t Total oil production in period t
TWI^t Total water injection in period t
y binary variable
ϕ an unrestricted continuous variable
θ, η, σ slack variables for MILP master subproblem

Subscripts and superscripts
L lower bound
o oil phase
U upper bound
R rock
w water phase

flow in the reservoir is highly nonlinear and spatiotemporal, which makes the optimization problem large, complex, and nonconvex. Guaranteeing the best solution becomes a huge challenge. Last, the inevitable discretization of the governing continuity equations renders the problem non-differentiable in the spatial domain and limits the application of derivative-based optimization algorithms.

The existing literature has studied three main approaches for optimal well placement: (a) mathematical programming (b) evolutionary and direct search (Afshari, Aminshahidy, & Pishvaie, 2011; Bouzarkouna, Ding, & Auger, 2012; Güyagüler & Horne, 2000; Onwunalu & Durlofsky, 2009; Wang, Ciaurri, Durlofsky, & Cominelli, 2012; Yeten et al., 2003), (c) gradient-based search (Ebadat & Karimaghaee, 2013; Sarma & Chen, 2008; Vlemmix, Joosten, Brouwer, & Jansen, 2009; Zandvliet, Handels, van Essen, Brouwer, & Jansen, 2008). Biegler and Grossmann (2004) and Grossmann and Biegler (2004) present an excellent overview of these methods, while our detailed literature survey (Tavallali, Karimi, Teo, Ayatollahi, & Baxendale, under review) and Nasrabadi, Morales, and Zhu (2012) specifically discuss their applications to well placement. While mathematical programming has been the

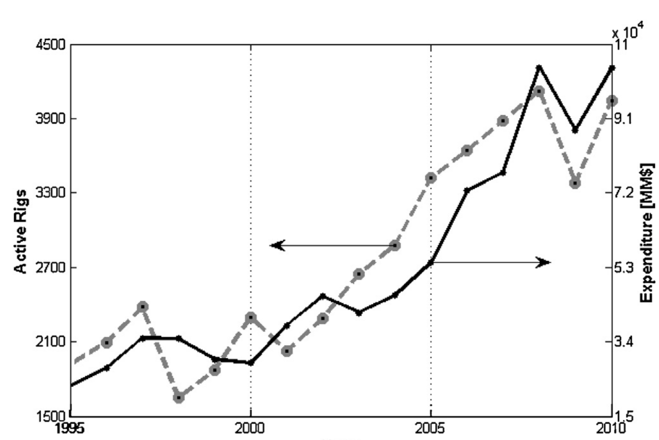

Fig. 1. Total upstream (exploration and development) expenditure of oil majors and number of active drilling rigs worldwide.

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