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IFAC-PapersOnLine 48-6 (2015) 248–253

Handling risk of uncertainty in model-based production optimization: a robust hierarchical approach

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Abstract: Model-based economic optimization of oil production suffers from high levels of uncertainty. The limited knowledge of reservoir model parameters and varying economic conditions are the main contributors of uncertainty. The negative impact of these uncertainties on production strategy increases and becomes profound with time. In this work, a multi-objective optimization problem is formulated which considers both economic and model uncertainties and aims to mitigate the negative effects i.e., risk of these uncertainties on the production strategy. The improved robustness is achieved without heavily compromising the primary objective of economic life-cycle performance. An ensemble of varying oil price scenarios and geological model realizations are used to characterize the economic and geological uncertainty space respectively. The primary objective is an average NPV over these ensembles. As the risk of uncertainty increases with time, the secondary objective is aimed at maximizing the speed of oil production to mitigate risk. This multi-objective optimization is implemented separately with both forms of uncertainty in a hierarchical or lexicographic way.

Keywords: Reservoir engineering, robust optimization, uncertainty handling, multi-objective optimization, lexicographic optimization

1. INTRODUCTION

Risk is a broad concept with various perspectives originating from different fields e.g., health, safety, environment etc. From an economic viewpoint, risk in the model-based optimization of water-flooding can be considered as the unpredicted variability or a potential loss of the expected economic objective. As the model-based optimization suffers from high levels of uncertainty see e.g., Van den Hof et al. (2012), the risk of loosing expected economic objective is also high. Risk management involves various approaches to mitigate the negative consequences of uncertainty e.g., Rockafellar (2007). In water-flooding optimization, robustness to the negative impact of uncertainties can be influenced by changing the production or control strategies. However, this improvement should be obtained without loosing sight of the main objective of maximizing the economic life-cycle performance of the water-flooding process.

Uncertainties are present in the reservoir models as well as in economic conditions. The geological uncertainty is profound because of the limited information contents from the measurement and production data about the true values of the model parameters. Furthermore, economic variables such as oil prices, interest rate etc., that are involved in different ways for quantifying the economic value of oil and gas reserves, fluctuate with time and can not be precisely predicted.

The negative consequences of uncertainties on the production and control strategy increase with time and become more profound with the length of the prediction horizon. By increasing the rate of oil production hence improving short-term gains mitigates risk of uncertainty on production strategy. An indirect or ad-hoc way to increase the speed of oil production by changing economic criteria is proposed in Van Essen et al. (2009b), where a hierarchical multi-objective optimization approach is introduced. NPV with a high discount factor is maximized as a secondary objective to improve short-term gains under the condition that the primary objective i.e., an un-discounted NPV stays close to it's optimal value. The optimality of the primary objective in this hierarchical approach is ensured by the availability of redundant degrees of freedom (DOF) with un-discounted NPV optimization. This multi-objective optimization does not consider uncertainty which is the core reason for the risk.

This work aims to address the question: can economic and geological uncertainty be explicitly included in such a hierarchical multi-objective optimization framework and will it provide better risk handling? The main focus will be to improve robustness without heavily compromising the primary objective of maximizing economic performance. An ensemble of varying oil price scenarios and geological model realizations are considered as a discrete approximation of economic and geological parametric un-

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.08.039

certainty space respectively. The primary objective is to improve economic performance by maximizing an average un-discounted NPV over the ensemble of varying oil price scenarios with single geological realization and later with the ensemble of geological realizations with fixed economic conditions. It is shown that in both cases, the optimal solution is non-unique, thus leaving the freedom to optimize a secondary objective without heavily comprising the primary objective in a hierarchical optimization framework. As the negative impacts of uncertainty grow with the time-horizon, the secondary objective function maximizes the rate of oil production by using an identical NPV, as in primary objective, but with a high discount factor. The results for this hierarchical multi-objective optimization are shown with both forms of uncertainties.

The paper is organized as follows: In Section 2, the model-based optimization is explained in detail. Handling risk of economic uncertainty is discussed in Section 3 with subsections on optimization of primary objective function and hierarchical optimization with simulation examples. A similar discussion and simulation examples are presented in Section 4 for handling risk of geological uncertainty. Section 5 presents some conclusions of the work.

2. MODEL-BASED ECONOMIC OPTIMIZATION

A model-based economic optimization approach has shown better economic life-cycle performance compared to the traditional reactive control strategy e.g., see Brouwer and Jansen (2004) and Jansen et al. (2008). The economic objective i.e., Net Present Value (NPV) in these studies can be mathematically represented as follows:

$$J = \sum_{k=1}^{K} \left[\frac{r_o \cdot q_{o,k} - r_w \cdot q_{w,k} - r_{inj} \cdot q_{inj,k}}{(1+b)^{\frac{t_k}{\tau_t}}} \cdot \Delta t_k \right] \quad (1)$$

where r_o, r_w and r_{inj} are the oil price, the water production cost and the water injection cost in $[\$/m^3]$ respectively. K represents the production life-cycle i.e., the total number of time steps k and Δt_k the time interval of time step k in $[days]$. The term b is the discount rate for a certain reference time τ_t. The terms $q_{o,k}, q_{w,k}$ and $q_{inj,k}$ represent the total flow rate of produced oil, produced water and injected water at time step k in $[m^3/day]$.

In this work, a gradient-based optimization approach is used where the gradients are obtained by solving a system of adjoint equations e.g., Jansen (2011). The gradient information is then used in a steepest ascent algorithm to iteratively converge to the (possible local) optimum.

3. HANDLING RISK WITH ECONOMIC UNCERTAINTY

Economic uncertainty has a time-varying dynamic nature and its negative effect on the production strategy increases with the time horizon. Among other economic uncertain variables in NPV, varying oil prices have the most dominant effect. Hence only oil price scenarios are used to characterize economic uncertainty.

3.1 Optimization of the primary objective function

In Van Essen et al. (2009a), a so-called robust optimization (RO) approach is introduced. It uses an ensemble of possible geological realizations to determine an average NPV over that set of realizations. In this work, RO approach is extended to incorporate the economic uncertainty with a single geological realization. The average NPV defined over the ensemble of varying oil price ensemble can be written as:

$$J_1 = \frac{1}{N_{eco}} \sum_{i=1}^{N_{eco}} J^i \quad (2)$$

where N_{eco} is the number of oil price realizations in an ensemble. Similar to the case of RO with geological uncertainty, from the formulation of the objective function in (2), calculating the gradient of the average NPV involves a linear operation. Hence, the gradient ∇J_1 can be computed as:

$$\nabla J_1 = \frac{1}{N_r} \sum_{i=1}^{N_r} \nabla J^i. \quad (3)$$

Here we consider J_1 to represent the primary objective of economic life-cycle performance optimization. One important point to consider here is that due to the linearity of the oil price in the NPV with the certainty of a geological model, the average of individual objective functions from each realization is equal to a single objective function with the average value of all oil price realizations as shown below:

$$\frac{1}{N_{eco}} \sum_{i=1}^{N_{eco}} [J(\mathbf{u}_k, \eta_i)] = J(\mathbf{u}_k, \frac{1}{N_{eco}} \sum_{i=1}^{N_{eco}} [\eta_i]) \quad (4)$$

where $\mathbf{u}_k$ is the input sequence and η_i is the i^{th} oil price realization in the ensemble.

3.2 Simulation example

All simulation experiments are performed using MRST, see Lie et al. (2012), which is a MATLAB based reservoir simulator. The details of simulation example with objective function (2) are given below:

Reservoir model and economic data: As the purpose of this simulation example is to show the effect of economic uncertainty on the optimal strategy, a single model realization of the Standard Egg model (Jansen et al. (2014)) is used. The standard egg model is a three-dimensional realization of a channelized reservoir produced under water flooding conditions with eight water injectors and four producers. The life-cycle of this reservoir model is 3600$[days]$. The absolute-permeability field and well locations of the model realization are shown in Fig. 1.

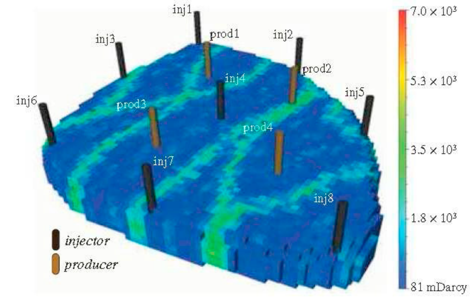

Fig. 1. Permeability field and well locations of the model realization