The National IOR Centre of Norway

Production optimization

Project 2.7.1

Project manager: Geir Nævdal

PhD students and postdocs: Aojie Hong, Micheal Oguntola, Yiteng Zhang

Other key personnel: Yuqing Chang, Alexey Khrulenko, Rolf J. Lorentzen, Andreas S. Stordal

Project duration: 2014-2021

Final Project Report

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1. Executive summary

The economic feasibility of implementing new IOR methods on a field needs to be evaluated, preferably taking the uncertainty in the reservoir description into account. In this project we have developed ensemble-based optimization methods to optimize the future production such that the economic potential of the reservoir is optimized. In the initial stage the focus was more on methodological development of ensemble-based methods for optimization, whereas at the final stage focus was shifted on demonstration on EOR cases of relevance for The National IOR Centre of Norway.

2. Introduction and background

Evaluating the economic potential of applying an IOR method would be a crucial decision step. In the evaluation, the strategies must be optimized, preferably taking the uncertainty in the reservoir description into account. Here we assume that the uncertainty description is available in the form of a set (an ensemble) of different reservoir models, and the strategy is optimized over those. By proper formulation of the optimization problem, one can search for optimal strategies taking environmental constraints into account.

Ensemble based tools for production optimization have been developed over the last couple of decades, with a special focus on waterflooding. In our setting it was important to expand this to include cases covering injection of smart water, CO_2, and polymer, with an additional focus on handling environmental issues.

In the initial part of the project most of the focus was on further development of the ensemble-based methods for optimization. In the final part, the focus was shifted towards practical applications such as optimal waterflooding, and optimization of EOR based injection strategies (polymer, smart water, and CO_2) injection. The latter part was done in strong interaction with the PhD student (Micheal Babatunde Oguntola) work in Task 7.2.12. This work also relied on the development of the OPM Flow simulator done in Task 6. Some of the simulations performed in this project also provided input to the environmental studies done in Task 4.

In addition, a study on upscaling from core to field was performed as part of this task. In that study it was focused on establishing a workflow for transforming knowledge available through IORCoreSim simulations into useful input for field scale simulators as ECLIPSE and OPM Flow. This was studied for polymer flooding.

One researcher, Andreas S. Stordal, spent part of his time visiting TU Delft and TNO as part of his work on this task. He spent approximately 6 months in Delft in the period 2014-2016. This cooperation led to the publication of [SSL16].

Through an external project funded by Equinor a study on optimization on the OLYMPUS field was performed. The work done in this study (see [CLNF20]) was taken further within the IOR center, leading to the conference paper [CNL20].

3. Results

In joint work between Andreas S. Stordal, IRIS, Slawomir P. Szklarz, TU Delft, and Olwijn Leeuwenburgh, TNO [SSN16] the mathematics (or statistics) of ensemble-based optimization was studied, and it was shown that the algorithm is a special case of an already well-defined natural evolution strategy known as Gaussian Mutation. A natural description of uncertainty in reservoir management arises from the use of an ensemble of history-matched geological realizations. A logical step is therefore to incorporate this uncertainty description in robust life-cycle production optimization through the expected objective function value.

The expected value is approximated with the mean over all geological realizations. It was shown that the frequently advocated strategy of applying a different control sample to each reservoir realization delivers an unbiased estimate of the gradient of the expected objective function. However, this procedure is more variance prone than the deterministic strategy of applying the entire ensemble of perturbed control samples to each reservoir model realization. To reduce the variance of the gradient estimate, an importance sampling algorithm was proposed and tested on a toy problem with increasing dimensionality.

Another theoretical advancement was presented by Michael B. Oguntola and Rolf J. Lorentzen in [OL21]. Here, a new efficient, robust, and accurate optimal solution strategy based on the exterior penalty function (EPF) method and the adaptive ensemble-based optimization (EnOpt) approach (with backtracking line-search technique) for non-linear constrained optimization problems is presented. This provides a more user-friendly strategy which mitigates the problem often faced with the current constraints handling technique utilized when using the EnOpt method to solve constrained problems of water or EOR flooding. To solve the problem, the EPF method is used to transform a given constrained optimization problem to a sequence of unconstrained subproblems and then sequentially solve the subproblems by unconstrained EnOpt procedure until convergence to the solution of the original problem. To demonstrate the advantage of the proposed methodology it is demonstrated on a number of test cases, including the 3D Reek reservoir field. The numerical results are compared with EnOpt using classical Lagrangian approach, as well as the traditional EnOpt. The results showed that the new proposed solution method has a fast convergence rate and is more accurate and robust.

Ensemble-based optimization is computationally intensive as it requires many reservoir simulations. To alleviate this problem, replacing the costly reservoir simulation model with a faster proxy model could lead to a significant reduction in computational time. This was investigated in [HBN17] where it was found that a capacitance-resistance model (CRM) can be a proxy model for waterflooding systems. The use of CRM-based models was illustrated and their pros and cons was investigated using synthetic 2D and 3D models. A selected proxy model is embedded into the proxy-model workflow. The results obtained from the proxy-model and traditional workflows were compared. It was found that the proxy-model workflow, leveraging a faster, but relevant, production model, significantly speeds up the optimization yet gives robust results that leads to a near-optimal solution. This work is part of Aojie Hong's PhD thesis [Hon17].

The paper "OLYMPUS optimization under geological uncertainty" written by Yuqing Chang, Rolf J. Lorentzen, Geir Nævdal and Tao Feng (Equinor) [CLNF20] presented our solution to the OLYMPUS benchmark challenge. The challenge was defined, with three different exercises: well control optimization, field development optimization, and joint field development and well control optimization. This paper presented solutions to the three exercises with two main optimization methods and problem-specific workflows. The main algorithms used in all three exercises are the ensemble-based optimization (EnOpt) and the line search derivative-free (LSDF) method. EnOpt is constructed for solving optimization problems where the uncertainty is represented by an ensemble of models, and in general it produced good results. However, we also found that the LSDF played an important role in quality checking the results obtained by EnOpt, and in some cases it provided superior results. The main part of this work was financed by Equinor in a separate project, and the work included significant interaction with Equinor. The application of the LSDF algorithm inspired the theoretical paper [Næv19].

Further investigations on the formulation of the optimization problem for waterflooding was done in [CNL20] where a different parameterization of the problem was used – the economical limits was used to determine the shut-in time for producers (i.e., the producers was shut-in when the well reached an optimized water-cut). With this parameterization it was possible to obtain higher NPV values than those obtained in [CLNF20].

Over the last decades several EOR methods have emerged, and corresponding models have been developed and implemented in increasingly more complex simulation tools. The paper [OL20] presents methodology and mathematical tools for optimizing and quantifying the value of EOR strategies, such as polymer, smart water or CO_2 . The developed methodology is demonstrated for polymer injection on medium to highly heterogeneous synthetic reservoir models with different complexity. The purpose of the work is to improve the understanding of the actual benefit of EOR methods, and to provide methodology that quickly allows users to find optimal production strategies that maximize the net present value (NPV). In [OL20], the control variables for the optimization problem are polymer concentration and water injection rates for each injecting well, and oil production rates or bottom hole pressures for the producing wells, over the exploration period. Each control variable is constrained with given production limitations. To account for the uncertainty in the reservoir model, an ensemble of geological realizations is considered, and a robust ensemble-based approximate gradient method (EnOpt) is utilized. The presented method is tested on three different synthetic reservoirs: a 2D five-spot field pattern with grid dimension 50×50×1, a 3D field provided by Equinor (the Reek field with dimension 40×64×14), and a 3D field provided by TNO (the OLYMPUS field with dimension 118×118×16). The first two fields have three phases (water, gas, and oil) and the third field has two phases (water and oil). For each case the optimal well controls for polymer flooding are found and then compared with convectional optimized continuous water flooding. The reservoir fluid flow is simulated using the Open Porous Media (OPM) simulator. However, it is worth noting that the optimization method is independent of the reservoir simulator used. Important findings of this study are the feasible control strategies for polymer EOR methods leading to an increased NPV, and comparison of the economic values for optimized polymer and traditional water flooding for the examples considered.

A study [Khr21] has been performed to investigate how an IORCoreSim sector models, reproducing core-scale experiments, can be used to set up full-field Eclipse/OPM models. The study demonstrated how polymer flood model in IORCoreSim can be translated into Eclipse. A set of keywords for the Polymer option of E100 was derived from a IORCoreSim core-scale polymer model. The developed Eclipse model was able to reproduce behavior of IORCoreSim.

A recommended practices document [CLN21] describing methodological developments for ensemble-based optimization of EOR processes has been prepared. The document gives an introduction to ensemble-based optimization and shows demonstrations on waterflooding and optimization of EOR processes.

4. Conclusions

This project has both improved the methodology for ensemble-based optimization, as well as demonstrated the use of ensemble-based optimization on waterflooding and while utilizing EOR methods. Three PhD students have been involved, one is finished (Aoije Hong), the other two (Michael B. Oguntola and Yiteng Zhang) are still in progress. At the time of writing, five journal papers have been published based on the results of the project. User involvement has been ensured by Equinor providing a synthetic field used in the study, as well as providing resources for additional related activities outside the NIORC.

5. Future work/plans

This Two PhD students are still working to complete their degrees. This will result in some further publications.

The manuscript "Robust Value Quantification of Enhanced Oil Recovery Methods using Ensemble-Based Optimization" with authors Micheal Oguntola and Rolf Lorentzen, is currently under review in SPE Reservoir Evaluation & Engineering.

This paper addresses mathematical tools for optimizing and ranking the value of the commonly utilized EOR methods. The methodology is demonstrated with Smart water, CO_2, and polymer EOR methods on synthetic 2D and 3D oil reservoirs. To capture the uncertainties in the reservoirs an ensemble of geological realizations is used.

The manuscript "A Natural Hessian Approximation for Ensemble Based Optimization" by Yiteng Zhang, Andreas S. Stordal and Rolf J. Lorentzen has been resubmitted to Computational Geosciences. The manuscript introduces a hessian approximation in combination with a trust-region approach to the ensemble based optimization framework. The methodology is tested on the Brugge field benchmark.

6. Dissemination of results

An NIORC Workshop on robust production optimization, value of information and decision making was held in September 2021. This workshop was very attractive from the user partners side, and at the most more than 80 participants were present at the same time. The workshop was held as a virtual event due to the corona situation, but still was very well received.

7. References

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