Optimization of Subsurface Flow

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Closed-loop reservoir management

• Hypothesis: recovery can be significantly increased by changing reservoir management from a ‘batch-type’ to a near-continuous model-based controlled activity

• Key elements:
  • Optimization under geological uncertainties
  • Data assimilation for frequent updating of system models

• Inspiration:
  • Systems and control theory
  • Meteorology and oceanography

• A.k.a. real-time reservoir management, quantitative reservoir management, integrated operations, smart fields, intelligent fields, ...
Closed-loop reservoir management

System (reservoir, wells & facilities)

Noise

Input

Output

Noise

Controllable input

Optimization

System models

Geology, seismics, well logs, well tests, fluid properties, etc.

Model updating

Predicted output

Measured output

Sensing
Robust flooding optimisation

System (reservoir, wells & facilities)

Optimization

System models

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Geology, seismsics, well logs, well tests, fluid properties, etc.

Input

Noise

Controllable input

Output

Predicted output

Measured output
Robust flooding optimisation

- Problem statement:
  What are the optimal well settings (e.g. tubing head pressures, injection rates, valve settings) over the producing field life to maximize economic performance (e.g. NPV) under geological uncertainty?

- Large scale: E.g., 20 wells, 20 years, monthly updates => 4800 optimization parameters

- Computationally hard: E.g., 100 geological realizations => 100 runs to compute one objective function value

- Most efficient techniques use gradients obtained with an adjoint formulation – beautiful but code intrusive
12-well example

- 3D reservoir
- High-permeability channels
- 8 injectors, rate-controlled
- 4 producers, pressure-controlled
- Production period of 10 years
- 12 wells x 10 x 12 time steps gives 1440 optimization parameters
- Optimisation of Net Present Value (NPV) $J$

$$J = \text{(value of oil} - \text{costs of water produced/injected)}$$

Van Essen et al., 2009
Robust optimisation

- Use ensemble of geological realisations (typically 100)

- Optimise expected value over ensemble
- Single strategy, not 100!
- If necessary include risk aversion (utility function)
- Computationally intensive

Van Essen et al., 2009
Robust optimization results

3 control strategies applied to set of 100 realizations: reactive control, nominal optimization, robust optimization

Van Essen et al., 2009
What to do without an adjoint?

With adjoint

Without adjoint

Thanks to Olwijn Leeuwenburgh (TNO)
Ensemble optimization (EnOpt)

- Adjoint-free: uses simulator as black box
- Approximate gradient-based method (debatable)
- Introduced by Lorentzen et al. (2006), Chen and Oliver (2008)
- Similar to other stochastic methods (Do & Reynolds 2013)
EnOpt - procedure

• Generate an ensemble of random control vectors (blue dots)

• Evaluate each ensemble member of controls (red dots)

• Estimate a gradient from the ensemble of function evaluations
Robust ensemble gradient estimate

Single geological model

Multiple geological models (~100)

Also 100 perturbations (1:100)

Is this magic?

E.g. 100 perturbations (1:100)

Also 100 perturbations! (1:1)
Is this magic?

• Pragmatic approach by Rahul Fonseca:
  • Fonseca, R.M. et al., 2015: Quantification of the impact of ensemble size on the quality of an ensemble gradient using principles of hypothesis testing. Paper 173236-MS, SPE RSS, Houston, USA, 22-25 February.

• Theoretical work with Andreas Stordal (IRIS):

• Theoretical work with Al Reynolds (Tulsa University):
  • Fonseca, R.M., Chen, B., Jansen, J.D. and Reynolds, A.C.: A stochastic simplex approximate gradient (StoSAG) for optimization under uncertainty. Submitted to *Int. J. for Num. Meth. in Eng.*

• Conclusion: theoretically open for discussion, but often very effective in practice if used with modified formulation
Robust gradient formulations

Original EnOpt (Chen, 2008; Oliver and Chen 2009):

\[ U = \begin{bmatrix} u_1 - \bar{u} & u_2 - \bar{u} & \ldots & u_M - \bar{u} \end{bmatrix}, \quad \bar{u} = \frac{1}{M} \sum_{i=1}^{M} u_i \]

\[ j = \begin{bmatrix} J_1(u_1, \theta_1) - \bar{J} \\ J_2(u_2, \theta_2) - \bar{J} \\ \vdots \\ J_M(u_M, \theta_M) - \bar{J} \end{bmatrix}^T \]

Modified EnOpt or StoSAG (Fonseca et al. 2014, 2016; based on Do & Reynolds, 2013):

\[ U_{mod} = \begin{bmatrix} u_1 - u^1 & u_2 - u^1 & \ldots & u_M - u^1 \end{bmatrix} \]

\[ j_{mod} = \begin{bmatrix} J_1(u_1, \theta_1) - J_1^1(u^1, \theta_1) \\ J_2(u_2, \theta_2) - J_2^1(u^1, \theta_2) \\ \vdots \\ J_M(u_M, \theta_M) - J_M^1(u^1, \theta_M) \end{bmatrix}^T \]
Objective function – effect of formulations

Net Present Value (USD) vs. Iterations

- Adjoint Gradient
- Modified EnOpt Gradient
- Original EnOpt Gradient
Objective function – different regions

Net Present Value (USD)

- Adjoint Gradient
- Modified EnOpt Gradient
- Original EnOpt Gradient

Fast increase => coarse gradient estimate required; higher ratio
Slow increase => fine gradient estimate required; 1:1 ratio OK
Conclusions & points not covered

- Scope: 0-10% NPV increase, mainly because of reduced water or gas production or reduced chemicals use in EOR
- Robust optimization is key. Can be modified to include risk aversion and/or economic uncertainty
- Adjoint most efficient. Modified EnOpt (StoSAG) good alternative if no adjoint available
- Specific optimization methods less important than workflow & human interpretation of results
- Need to combine long-term recovery optimization with short-term production optimization
- Limited uptake in industry. However, much interest in well location, scheduling, FDP optimization
Acknowledgments

- Dr. Gijs van Essen (TU Delft, now with Shell)
- Dr. Rahul Fonseca (TU Delft, now with TNO)
- Prof. Paul van den Hof (TU Eindhoven)
- Dr. Olwijn Leeuwenburgh (TNO)
- Prof. Al Reynolds (Tulsa University)

- The ISAPP Knowledge Centre, a joint project of TNO, TU Delft, ENI, Statoil and Petrobras

- The Recovery Factory program, a joint project of TU Delft and Shell

- The National IOR Centre of Norway for sponsoring several visits of Andreas Stordal