Optimization of Horizontal/Deviated Well Placement and Control for CCS Using Upscaled Models

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Motivation

Facilitate safer trapping

- Structural & stratigraphic trapping
- Residual CO₂ trapping
- Increasing storage security
- Solubility trapping
- Mineral trapping

Based on IPCC, 2005
Objective function and constraints

- Optimization problem
  \[
  \min_{u \in U} f(x, u) \quad \text{s.t.} \quad g(x, u) = 0, \quad C(x, u) = 0
  \]
  \(x\): state variables \(p, S\); \(u\): well placement variables \(u_l\) and time-varying injection fractions \(u_c\)

- Minimization of time-averaged mobile CO\(_2\) fraction
  \[
  f = \frac{1}{T} \int_{t=0}^{T} \left( \frac{m_m}{m_t} \right) \, dt
  \]

- Constraints \([C(x,u)]\)
  - Geometric: min/max well length, min well-to-well and well-to-boundary distances
  - Controls: total injection rate, max BHPs, injected mass retained in aquifer
Integrated optimization framework

- Initialization
  - Repair procedure
    - Function evaluation
      - Penalty function
        - Filter method
          - Output solution
            - Yes
              - Termination criterion
                - No
                  - Update solution with core optimizer

- Appropriate constraint treatment
  - Repair procedure
  - Penalty function
  - Filter method
Repair procedure (Volkov & Bellout, 2018)

- Minimize total constraint violations
- Minimize distance between the repaired solution and original solution

Before repair ($C > 0$)

After repair ($C = 0$)
Integrated optimization framework

- **Initialization**
- Repair procedure
- Function evaluation
- Penalty function
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- Update solution with core optimizer

- **Appropriate constraint treatment**
  - Repair procedure
  - Penalty function
  - Filter method

- **Derivative-free optimization algorithm**
  - Particle swarm optimization
Particle swarm optimization (PSO)

\[ u_{i}^{k+1} = u_{i}^{k} + v_{i}^{k+1}, \forall i \in 1, \ldots, N \]

\[ v_{i}^{k+1} = \omega v_{i}^{k} \quad \text{(inertial component)} \]

\[ + c_{1} D_{1} (u_{i}^{Pbest} - u_{i}^{k}) \quad \text{(social component)} \]

\[ + c_{2} D_{2} (u_{Gbest}^{Gbest} - u_{i}^{k}) \quad \text{(cognitive component)} \]

- Population based algorithm
  - Optimizations typically require thousands of simulations
  - Can be **expensive** for high-fidelity models, even with parallelization
Integrated optimization framework

- **Initialization**
- **Repair procedure**
- **Function evaluation**
- **Penalty function**
- **Filter method**

**Termination criterion**

- Yes ➔ **Output solution**
- No ➔ **Update solution with core optimizer**

- **Appropriate constraint treatment**
  - Repair procedure
  - Penalty function
  - Filter method

- **Derivative-free optimization algorithm**
  - Particle swarm optimization

- **Multifidelity treatment**
  - Low-fidelity: 10 runs (select 5 best)
  - High-fidelity: 1 run
High-fidelity aquifer model

- **Storage aquifer**
  - Grid: 105 x 105 x 30
  - Dimensions: 16.2 km x 16.5 km x 0.57 km
  - Gaussian log-perm field (following Crain et al. 2022)
  - Represent overall domain: 234 km x 234 km x 0.57 km

- **Wells**
  - Deviated/Horizontal wells in 3D
  - 4 surface-rate controlled injectors
    - BHP capped at 276.3 bar (4007 psi)
  - Field injection target = 4 MT/yr
  - Injection period = 30 yrs
  - Shut-in period = 20 yrs

- **Simulator**
  - Eclipse 300 CO2STORE
  - Rel perm hysteresis & dissolution included

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Energy Science & Engineering
Upscaling method

- **Transmissibility upscaling**
  - Global
  - Single-phase
  - Slightly compressible system
  - Pseudo-steady state (PSS)

\[
\nabla \cdot \left( \frac{k}{\mu} \nabla p \right) = q + \varphi c \frac{\partial p}{\partial t}
\]

PSS \( \Rightarrow \frac{\partial p}{\partial t} \) = constant

- **Upscaling schemes**: 3 x 3 x 3 and 5 x 5 x 5

\[
T_{m+1/2}^* = \frac{\sum_{l=1}^{3} (q^f)_l}{(p^f)_m - (p^f)_{m+1}}
\]
Upscaling method

- Well treatment

**Method 1**
\[ T^* + WI^* \]

**Method 2**
\[ T^* + LGR \]

\[ WI^*_m = \frac{q^{w,f}}{\langle p^f \rangle_m - p^{w,f}} \]
Time-averaged mobile CO$_2$ fraction

300 solutions

\begin{align}
\text{RMSE} &= 0.158 \\
\text{5x5x5 } T^* + WI^*
\end{align}

\begin{align}
\text{RMSE} &= 0.098 \\
\text{5x5x5 } T^* + \text{LGR}
\end{align}
Error box plot

300 solutions

Time-averaged mobile CO₂ fraction
Error box plot

300 solutions

- Acceptable error
- Faster runtime
  (~1.5x faster than 3 x 3 x 3 $T^*+\text{LGR}$)

Accuracy in maximum BHP is important for constraint satisfaction
High-fidelity base-case

Horizontal wells in layer 25

Uniform injection in all wells
Base-case

5 x 5 x 5 $T^* + \text{LGR}$
21 x 21 x 6 (+LGRs)

3 x 3 x 3 $T^* + \text{LGR}$
35 x 35 x 10 (+LGRs)

High-fidelity
105 x 105 x 30
Optimization setup

- Place **4 wells (with 5 control periods)** to minimize time-averaged mobile CO$_2$ fraction
- Optimization variables: **44** (24 well location, 20 injection rate fraction)
- Constraints:
  - Minimum and maximum well lengths: 823 m and 3000 m
  - Minimum well-to-well and well-to-boundary distance: 1646 m
  - Controls: total injection rate achieved, injected mass retained in aquifer, max BHPs
- Switch/termination criteria: <1% improvement after 20 iterations
- PSO with population of 44; runs are fully parallelized
- Average timings:
  - High-fidelity runs require ~54 min/run
  - Low-fidelity ~1.5 min/run (**36x speedup**)
PSO multifidelity optimization

- 1 Effective Function Eval = 1 HF run (equivalent to 36 LF runs)
- AF: all-fine-scale (HF) runs in optimization
- Multifidelity HF run initialized with 44 best solutions from best 5 LF runs
- Better solution, with less computational effort, using multifidelity (MF) approach
- All geometric and rate constraints satisfied in all optimized solutions
Comparison between optimized solution and base-case

Minimization of time-averaged mobile CO$_2$ fraction

- Base-case: 0.5241
- Best HF run: 0.2724
- MF run: 0.2714
PSO multifidelity optimized solution (shown at HF)

Minimization of time-averaged mobile CO$_2$ fraction

Max CO$_2$ saturation  
3D CO$_2$ field  
Well controls
Summary and conclusions

- Developed a transmissibility upscaling approach for CCS simulations based on global, single-phase, pseudo-steady-state solutions of the pressure equation. Near-well LGR representations are incorporated in the upscaled models.

- Optimized time-averaged mobile CO₂ fraction with realistic constraints using a multifidelity approach.

- Multifidelity optimized solution is comparable to the solution from all fine-scale optimization, with significantly less computational effort.
Future work

- Consider vertical injection wells (not considered here due to well-length constraint)
- Apply surrogate models to reduce the number of simulations required for optimization
- Include geomechanical effects
- Apply treatments for handling geological uncertainty
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