

# Recent Developments in Model-Based Optimization and Control of Subsurface Flow in Oil Reservoirs

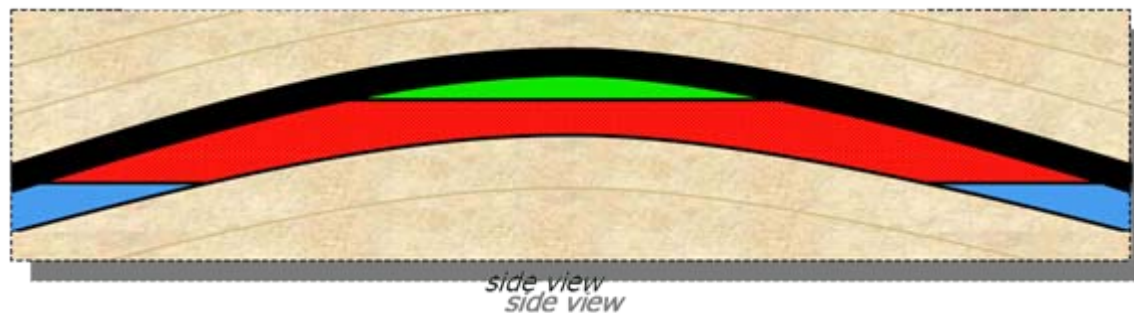
Paul M.J. Van den Hof, Jan Dirk Jansen, Arnold Heemink

Keynote lecture,  
1<sup>st</sup> IFAC Workshop on Automatic Control in  
Offshore Oil and Gas Production,  
31 May- 1 June 2012, Trondheim, Norway



# Oil Production

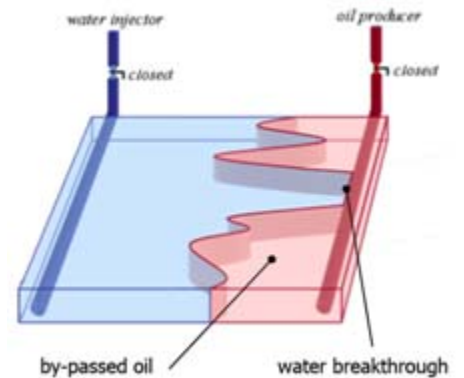
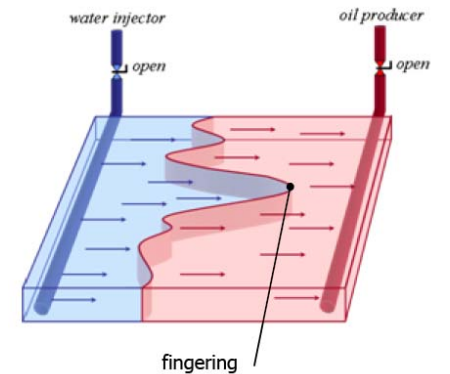
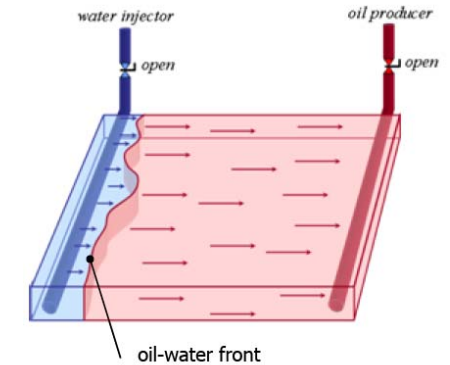
- Production from Oil Reservoirs
  - Porous rock with oil in pores
  - Geological structure heterogeneous
    - Very different rock properties within reservoir
  - $10^1 - 10^4$  km<sup>2</sup> in size
  - $10^3$ m –  $10^4$ m underground
  - Difficult locations



- cap rock
- water bearing reservoir rock
- non- reservoir rock
- oil bearing reservoir rock
- gas bearing reservoir rock

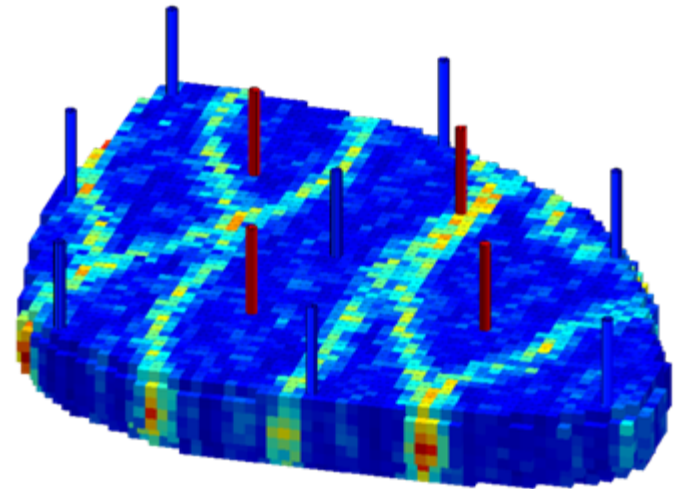
# Oil Production

- Oil Production goes through multiple stages
  - Primary production (5-15%)
  - Secondary production
  - Tertiary production
- **Waterflooding** (WF) popular secondary production process
  - Reservoir pressure support
  - Sweeping the reservoir
- Essentially a batch process
  - Life time in the order of decades
  - Potential to recover **20-70%** of the oil
  - Limited in practice by lack of operational strategy

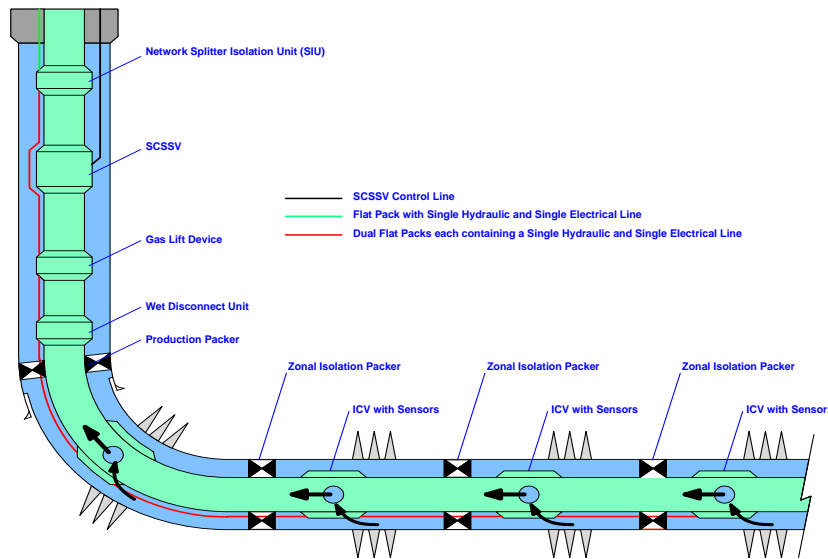


# Reservoir characteristics

- 3D
- heterogeneity of reservoir
- flow dynamics determined by geological structure (permeability)



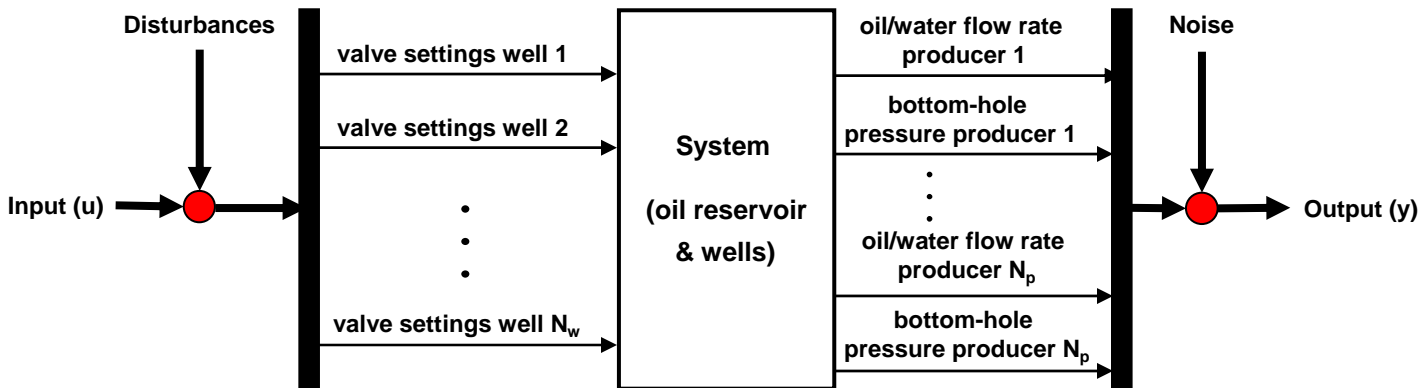
(Gijs van Essen et al.,  
CAA 2006)



- Smart wells allow control over (distributed) local valve settings in injectors and producers, and local measurements.

# The Objective

- **Inputs:** control valve settings of the wells (injectors and producers)
  - Smart wells: multiple (subsurface) valves
- **Outputs:** (fractional) flow rates and/or bottomhole pressures
  - Smart wells: multiple (subsurface) measurement devices



Objective: Economic operational strategy that optimizes performance (life cycle)

# Contents

- Introduction
- Closed-loop reservoir management
- Current limitations and challenges
  
- Robust optimization
- Balancing long-term and short-term objectives (hierarchical)
- Parameter estimation
- Time-scale separation – 2-level approach
- Control-relevant models
  
- Discussion

# The models

Mass balance:

$$\nabla \cdot (\rho_i u_i) + \frac{\partial}{\partial t}(\phi \rho_i S_i) = 0 \quad i = \{o, w\}$$

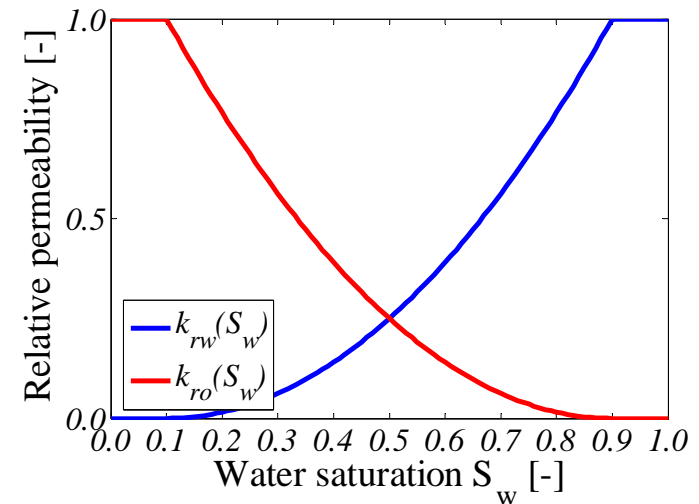
Momentum (Darcy's law):

$$u_i = -k \frac{k_{ri}}{\mu_i} \nabla p_i \quad i = \{o, w\}$$

**Variables:**  $p_o, p_w, S_o, S_w$

Saturations satisfy:  $S_o + S_w = 1$

Simplifying assumptions, a.o.:  $p_o = p_w$



# Discretization in space and time

After discretization in space (and time):

$$g(x_{k+1}, x_k, u_k, \theta) = 0$$

$$y_k = h(x_k)$$

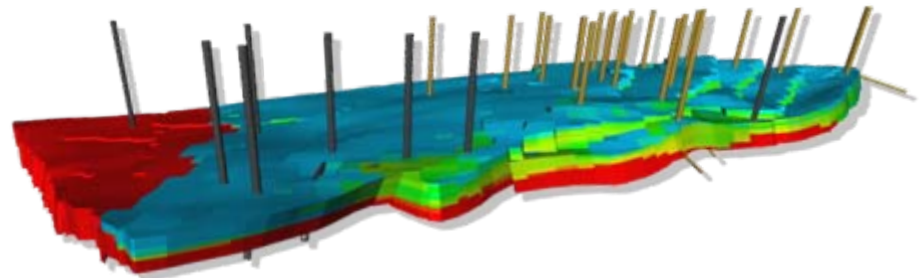
$$\dim(x) \approx 10^4 - 10^6$$

$$y_k^T = [p_{well}^T \quad q_{well,o}^T \quad q_{well,w}^T]$$

$$x_k^T = [p_o^T \quad S_w^T]$$

and  $\theta$  typically the permeabilities in each grid block

- Models are large-scale
- Nonlinear
- Long simulation time
- Typically used off-line



# Model-based Life-Cycle Optimization

Net present value (NPV):

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

Optimization problem:

$$\begin{aligned} & \max_{\mathbf{u} \in Q} J_K(\mathbf{u}, x_0), \\ & \text{subject to } \mathbf{g}(\mathbf{u}, \mathbf{x}) = 0, \quad x_0 = \bar{x}_0, \\ & \text{and } \mathbf{c}(\mathbf{x}, \mathbf{u}) \leq 0, \quad \mathbf{d}(\mathbf{x}, \mathbf{u}) = 0 \end{aligned}$$

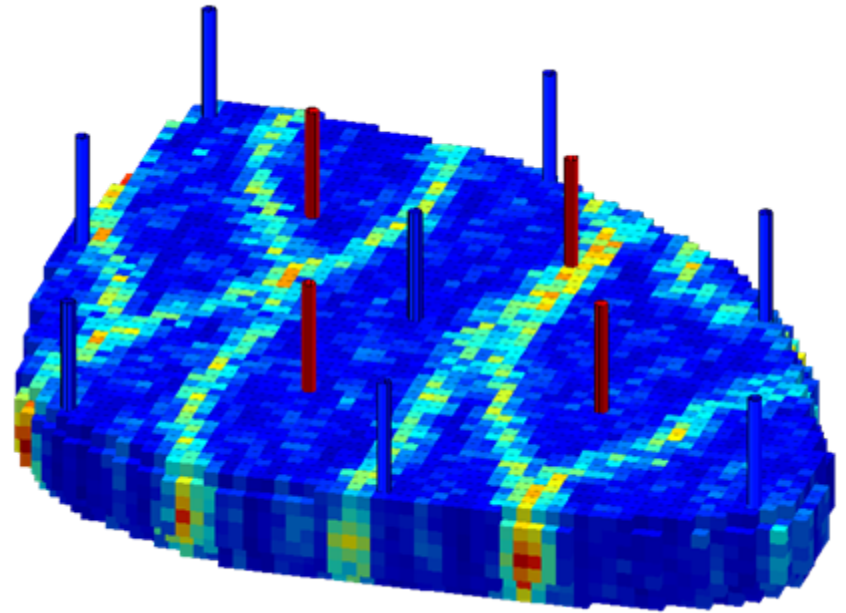
Non-convex optimization, solved by gradient-based method:  
Adjoint-variables calculation through backward integration of  
the related (Hamiltonian based adjoint) equation.

(feasible for systems of this size)

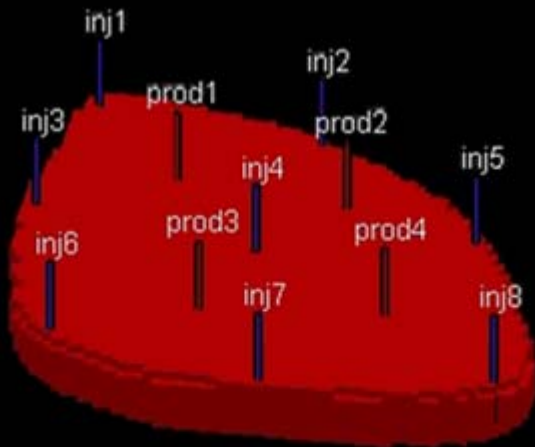
[Ramirez, 1987; Brouwer &  
Jansen, SPE J, 2004]

# 12-well example

- 3D reservoir
- 8 injection / 4 production wells
- Period of 10 years
- High-permeability channels
- 18.553 grid blocks
- Minimum rate of 0.1 *stb/d*
- Maximum rate of 400 *stb/d*
- No discount factor
- $r_o = 20$  *\$/stb*,  $r_w = 3$  *\$/stb* and  $r_i = 1$  *\$/stb*
- Optimization of economic benefit
- Model-based optimal control with a known model



(Gijs van Essen et al.,  
CAA 2006)



*Reactive Control*

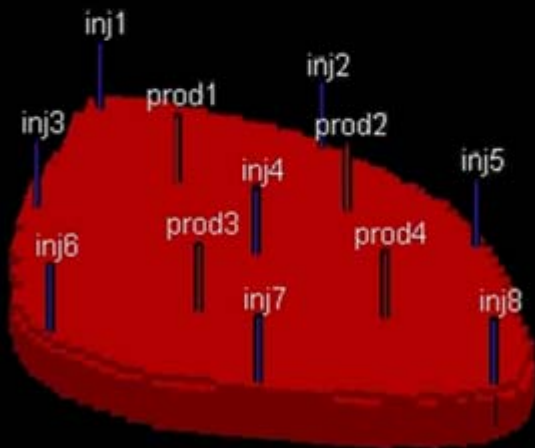
*flow-rate*

- inj1
- inj2
- inj3
- inj4
- inj5
- inj6
- inj7
- inj8
- prod1
- prod2
- prod3
- prod4

Cumulative Data

Oil Production:  $0.00 \times 10^6$  bbl  
 Water Production:  $0.00 \times 10^6$  bbl  
 Water Injection:  $0.00 \times 10^6$  bbl

**Revenue: 0.0 M\$**



*Optimal Control*

*flow-rate*

- inj1
- inj2
- inj3
- inj4
- inj5
- inj6
- inj7
- inj8
- prod1
- prod2
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Cumulative Data

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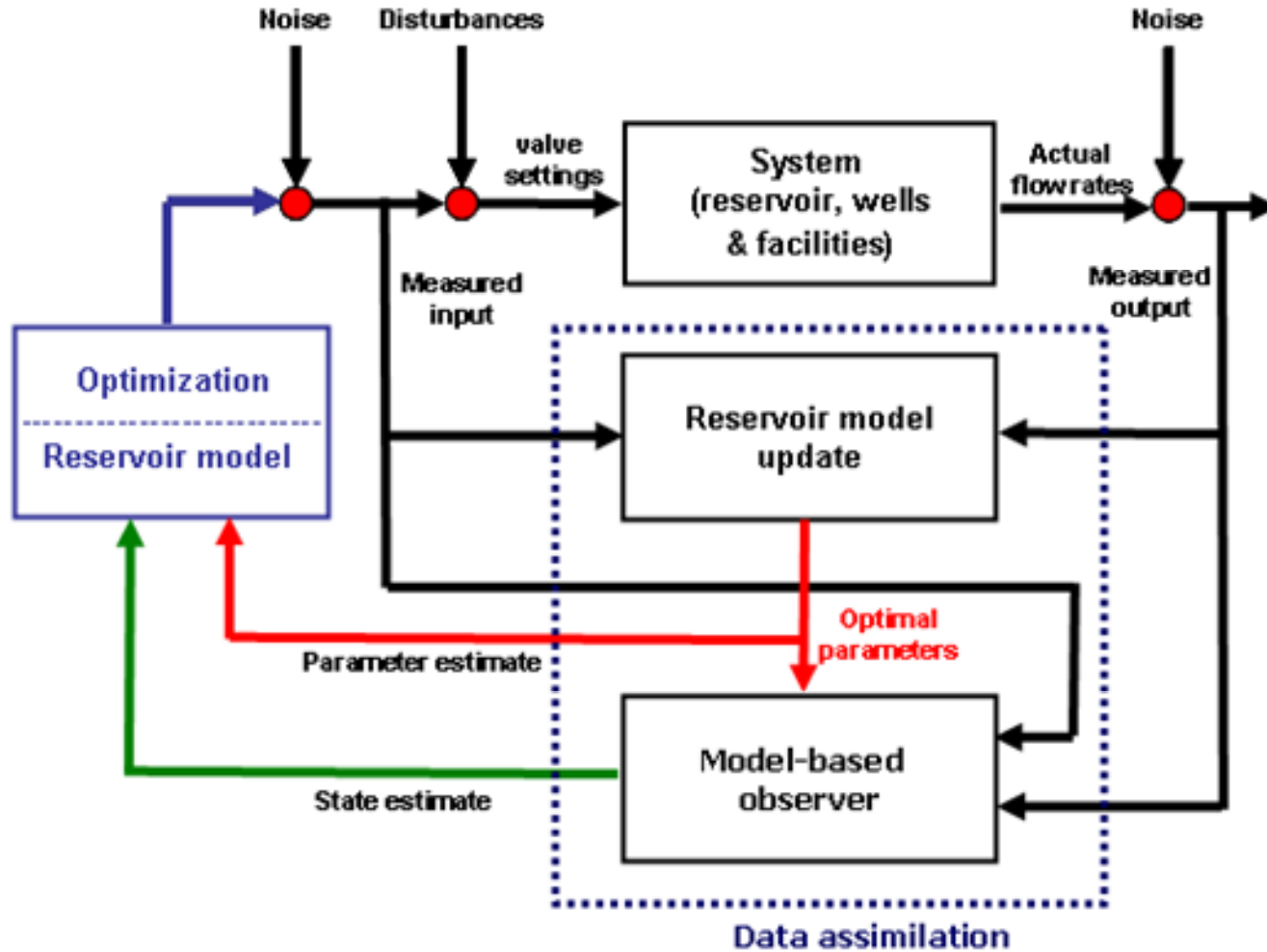
**Revenue: 0.0 M\$**

*time = 0.00 year*

# Closed-loop Reservoir Management

- Moving from (batch-wise) open-loop optimization to **on-line closed-loop control**
  - State estimator
  - Optimized plant input through NMPC in receding/shrinking horizon
  - No trajectory following but dynamic RTO
- On-line estimation of states (and model parameters) through **Ensemble Kalman filter (EnKF)** (Evensen, 2006)  
Kalman type estimator, with analytical error propagation replaced by Monte Carlo approach

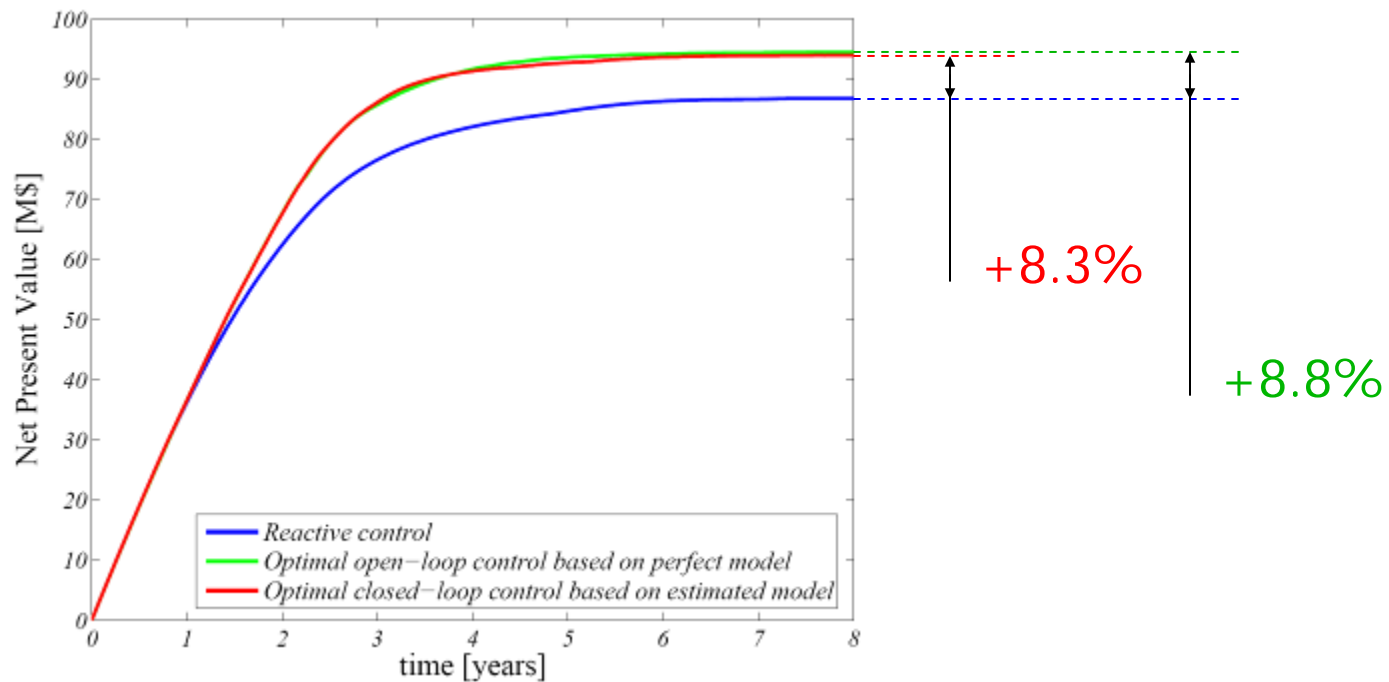
# Closed-loop Reservoir Management



# Closed-loop simulation example

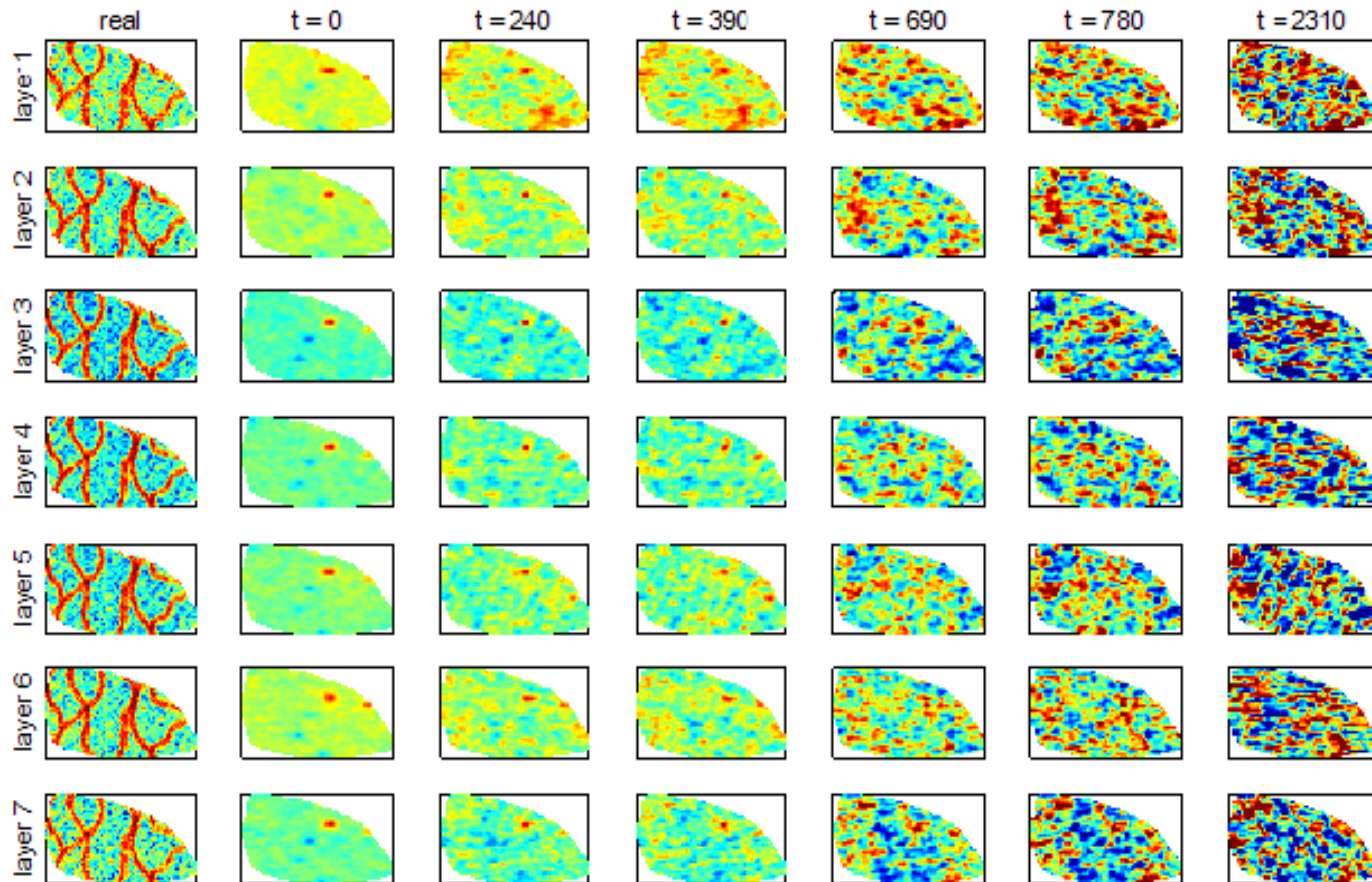
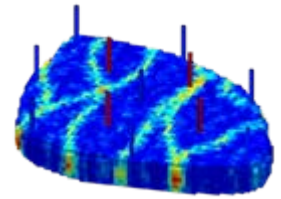
## Results

- 3 study cases: reactive control, optimal open-loop control based on perfect ('reality') model, optimal closed-loop control



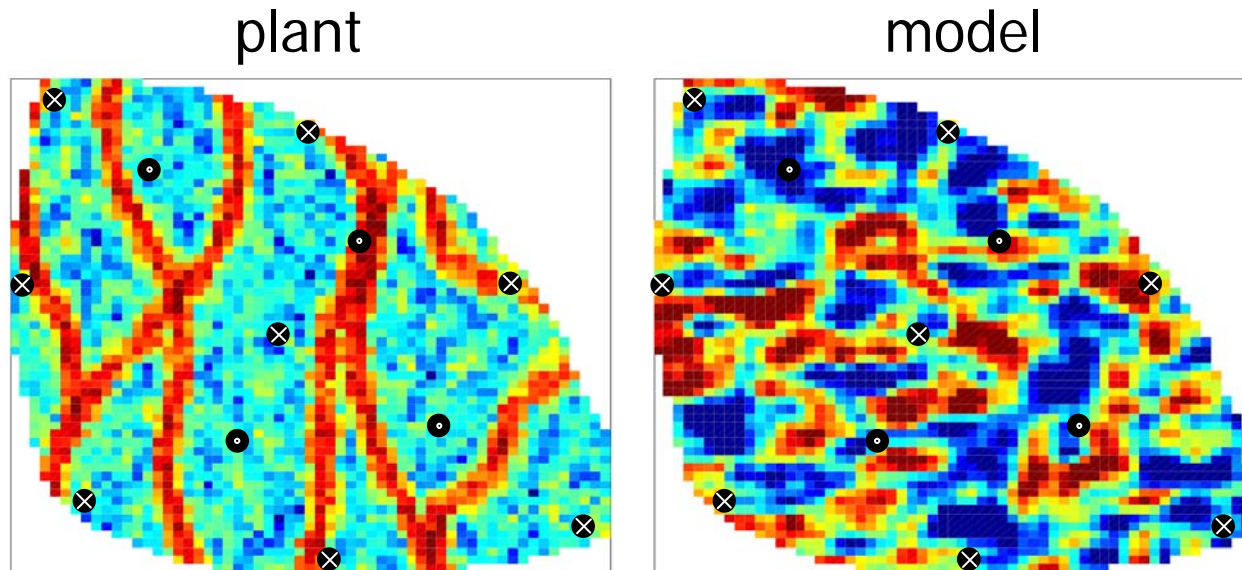
# Closed-loop simulation example

Ensemble updates at different times



# Closed-loop reservoir management

Relatively poor looking models may work quite well!



# Current limitations and challenges

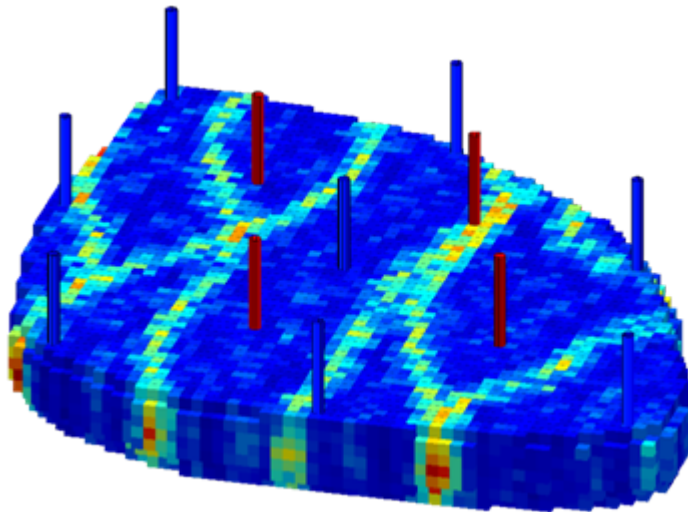
- Model uncertainty      uncertain geology
- Model complexity      geological vs control models
- Measurement data      limited knowledge
- Nonlinearity      dynamics change over lifetime
- Process configuration      (dynamic) well placement

# Contents

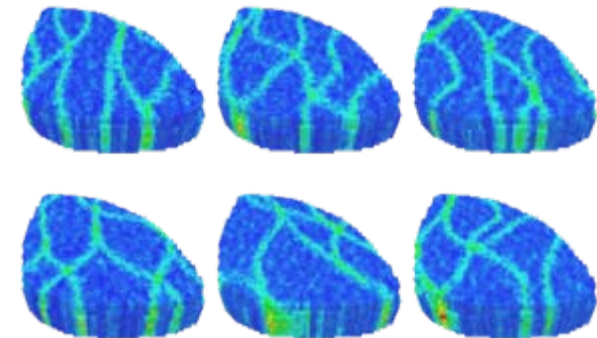
- Introduction
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- Current limitations and challenges
  
- **Robust optimization**
- Balancing long-term and short-term objectives (hierarchical)
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# Robust optimization

- Reservoir models / permeability structure are highly uncertain



model realizations



- Use 100 realizations in a max-mean approach:

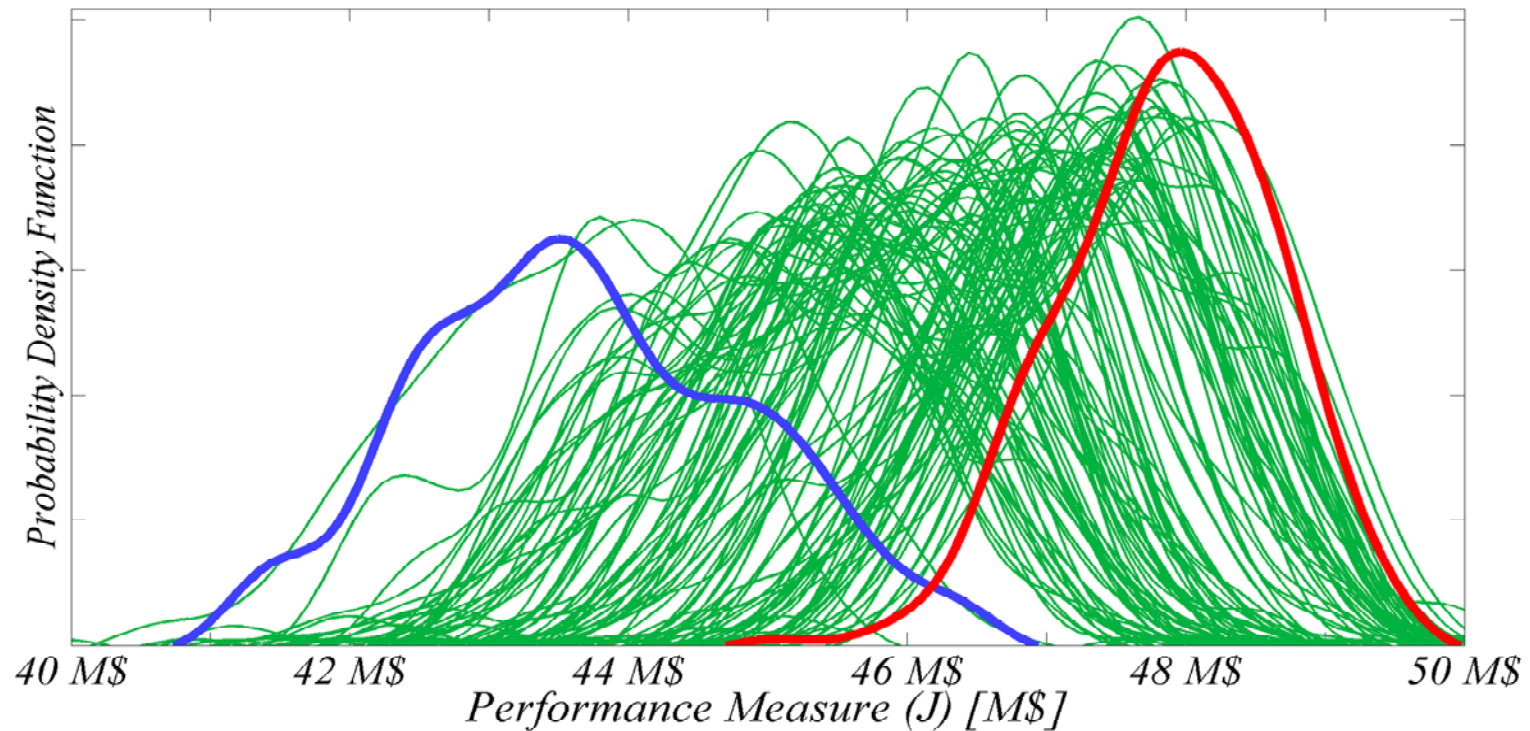
$$\max_{\mathbf{u}} \left( \frac{1}{M} \sum_{i=1}^M J_K(\mathbf{u}, \theta_i) \right)$$

[Gijs van Essen et al., Proc. CCA, 2006]

# Robust optimization example

3 control strategies applied to set of 100 realizations:

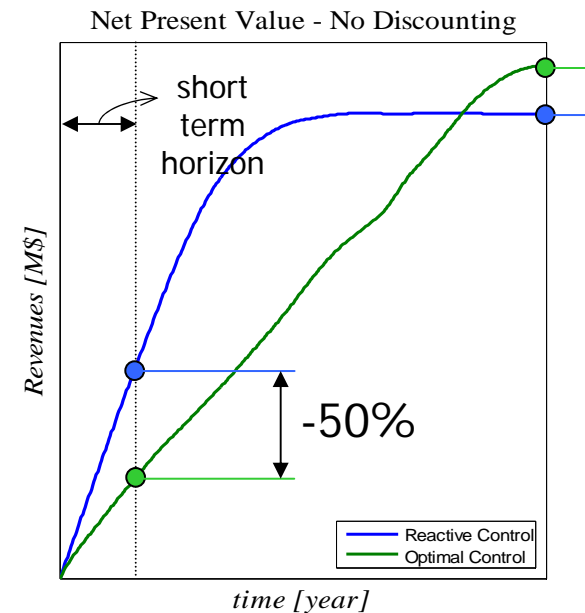
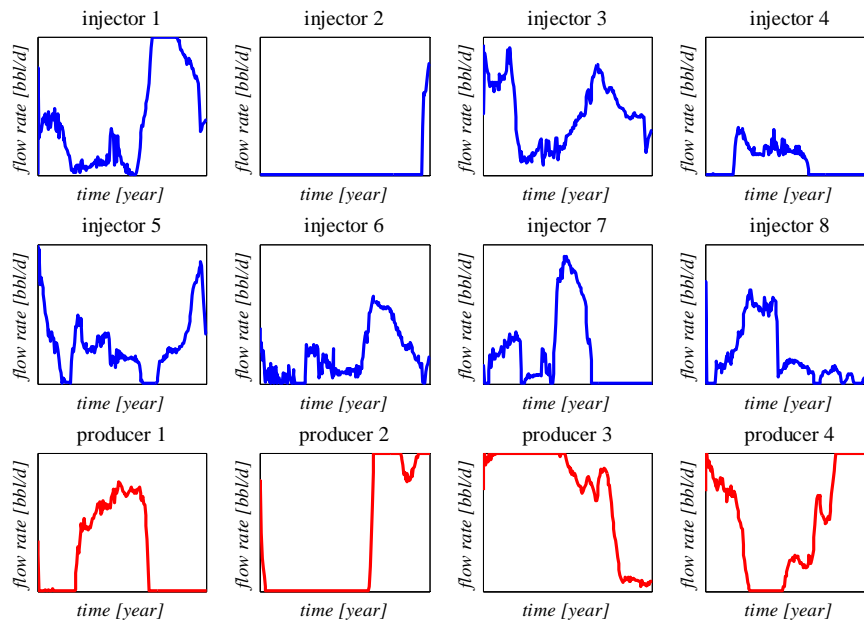
- reactive control, nominal optimization (100 strategies), robust optimization



[Van Essen et al, SPE J, 2009]

# Hierarchical optimization

- Focussing on life-time (long-term) NPV has limitations:
  - Compromise in short-term production
  - Erratic operational strategy



[Van Essen et al, SPE J, 2009]

# Hierarchical optimization

- Distinguish two different objective functions:

$$\mathbf{u}^* = \arg \max_{\mathbf{u}} J_K^{(1)}(\mathbf{u}, x_0)$$

with  $J_K^{(1)}$  the **long-term NPV**

- Additionally optimize for short-term production:

$$\tilde{\mathbf{u}}^* = \arg \max_{\mathbf{u}} J_K^{(2)}(\mathbf{u}, x_0)$$

such that  $J_K^{(1)}(\mathbf{u}, x_0) \geq J_K^{(1)}(\mathbf{u}^*, x_0) - \varepsilon$

with  $J_K^{(2)}$  the **short-term NPV**

Utilize degrees of freedom in the input to optimize short-term production

[Van Essen et al, SPE J, 2011]

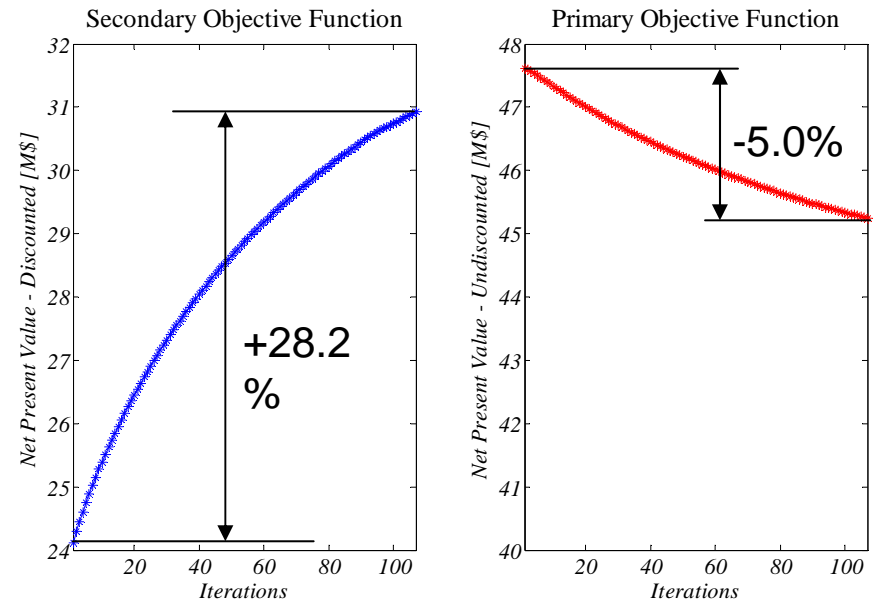
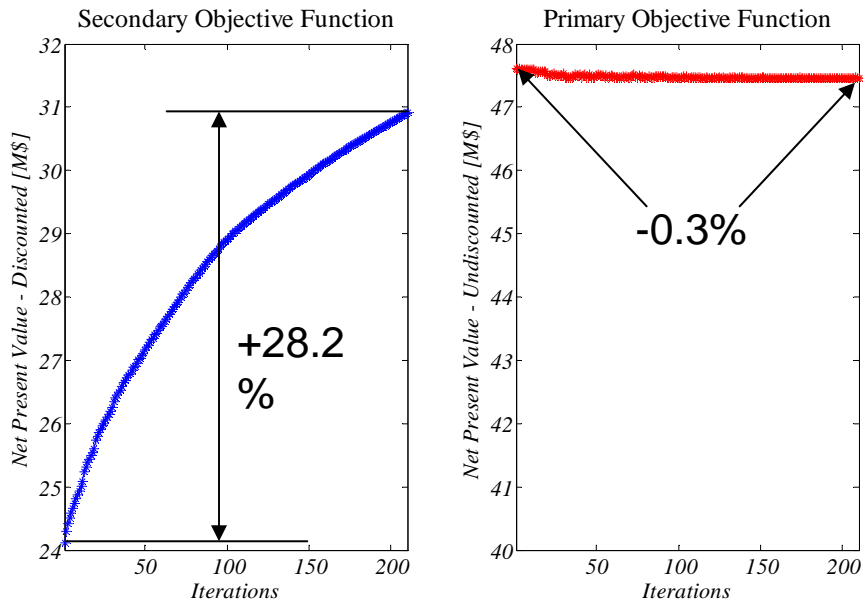
# Objective function with ridges



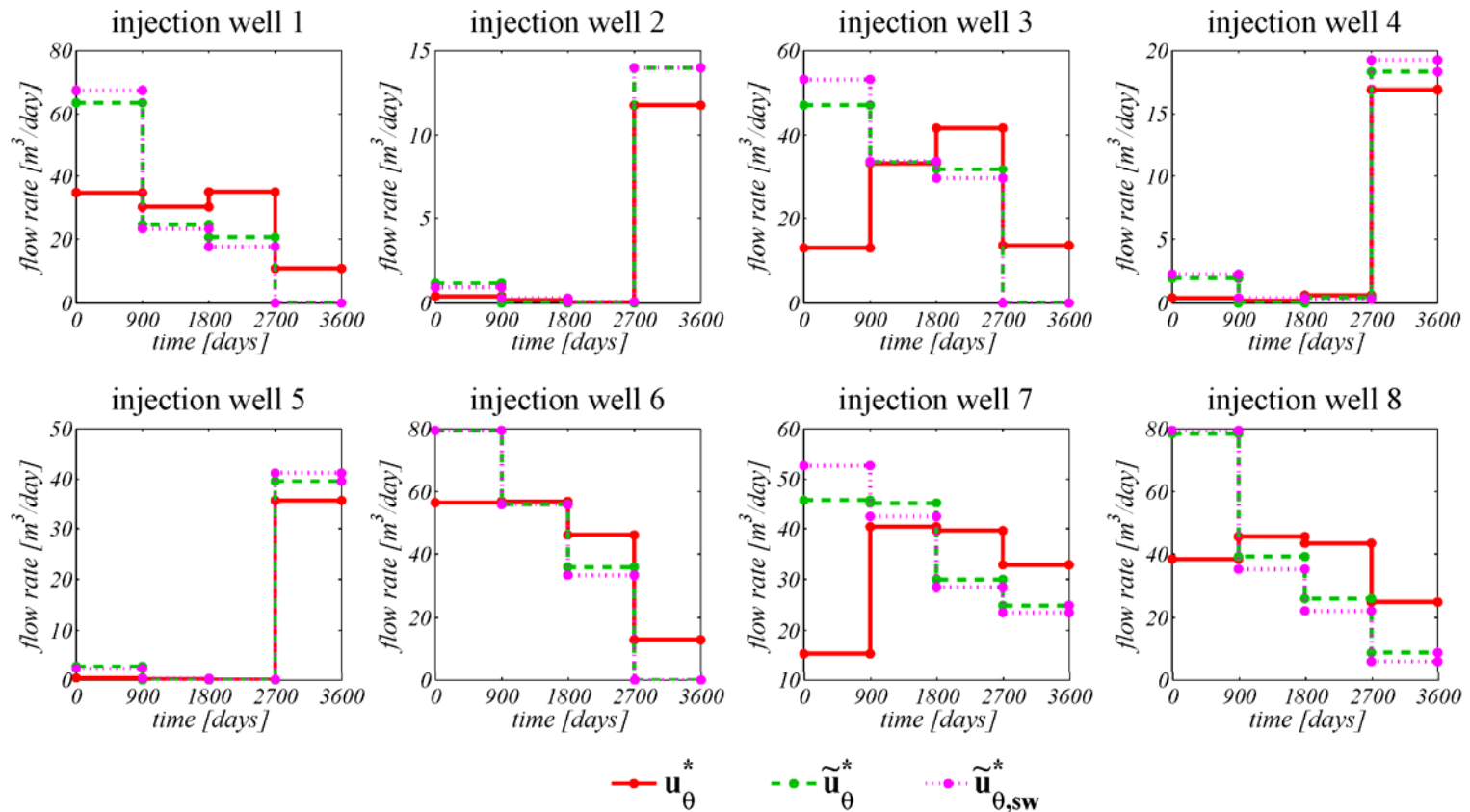
# Hierarchical optimization example

Optimization of secondary objective function - constrained to null-space of primary objective

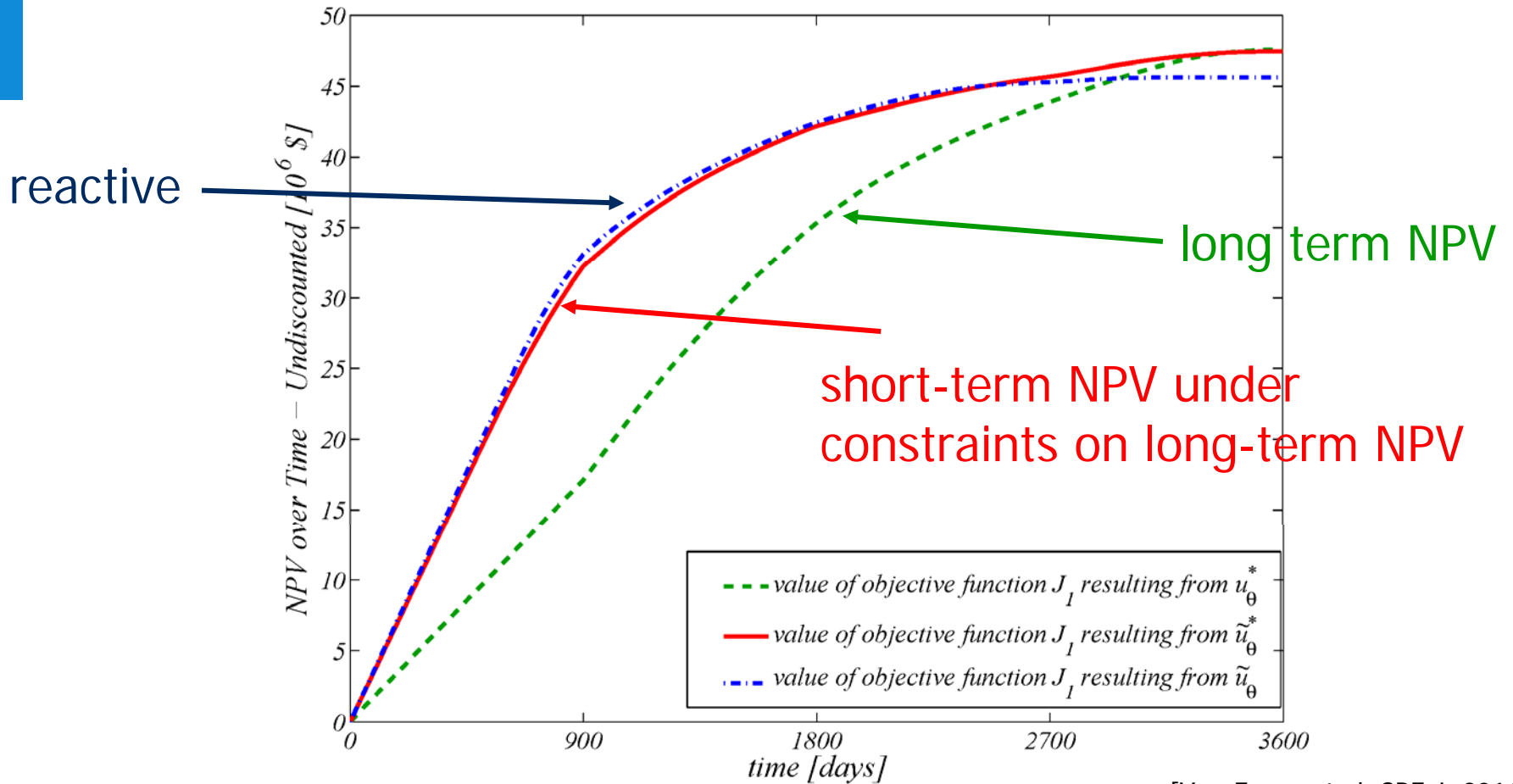
Optimization of secondary objective function - unconstrained



# Hierarchical optimization example



# Hierarchical optimization example



[Van Essen et al, SPE J, 2011]

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- Robust Optimization
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- **Parameter estimation**
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# Parameter Estimation

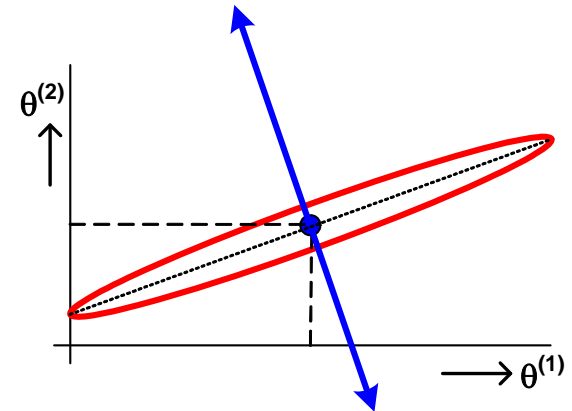
## Typical approach in geological models:

- Use EnKF to estimate states
- Consider parameters (grid-block permeabilities) as extended states
- Estimate **parameters and states**, based on an initial ensemble
  - Data not sufficiently informative to estimate all parameters
  - Parameters are updated only in directions where data contains information

# Parameter Estimation

Bayesian approach:

$$V_p(\theta) := V(\theta) + \frac{1}{2}(\theta - \theta_p)P_{\theta_p}^{-1}(\theta - \theta_p)$$



Lack of identifiability: Hessian of  $V_p$  is poorly conditioned

- The Bayesian estimate becomes heavily determined by priors

Parametrization can be reduced by projecting unto the (locally) identifiable subspace [Van Doren et al, IFAC 2008,2011]

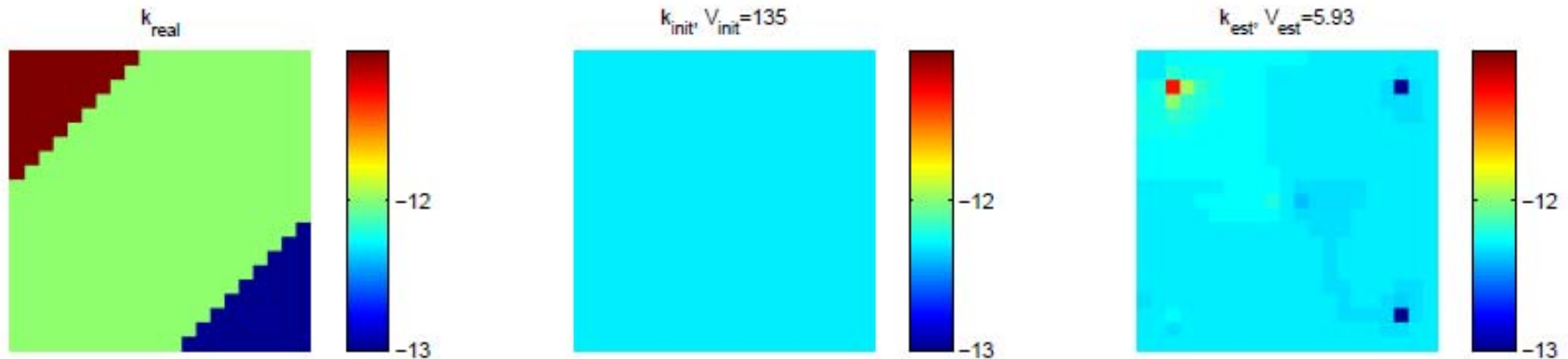
Several alternatives for reduction of parameter space

[Durlovsky et al., 1996; Zhang et al. 2008; Van Doren, 2010; Jafarpour & McLaughlin, 2008,2009; Tavakoli & Reynolds, 2010]

Capturing long-term behaviour (nonlinear) is the challenge

# Simple reservoir example

Using the reduced parameter space –iteratively- in estimation:



exact field

initial estimate  
(local point)

final estimate

## Observation:

Only grid block permeabilites around well are identifiable.

# Time-scale separation – Two-level approach

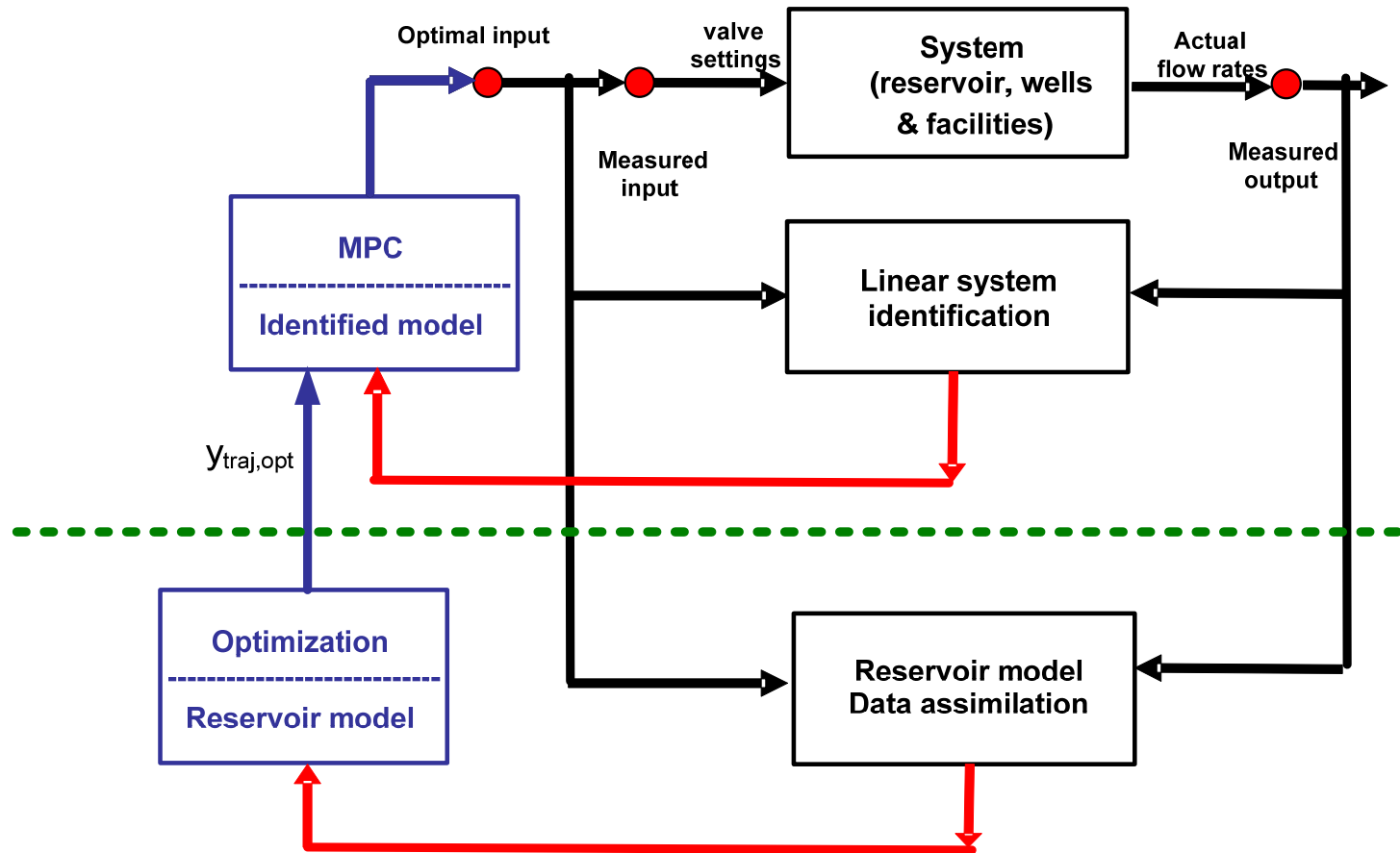
## Reasoning

- Optimization on the basis of **nonlinear reservoir models** suffers from model uncertainties
- Optimization on the basis of **identified (linear) models** suffers from a lack of predictive capabilities beyond the –local– measurement interval

 **Combine the two**

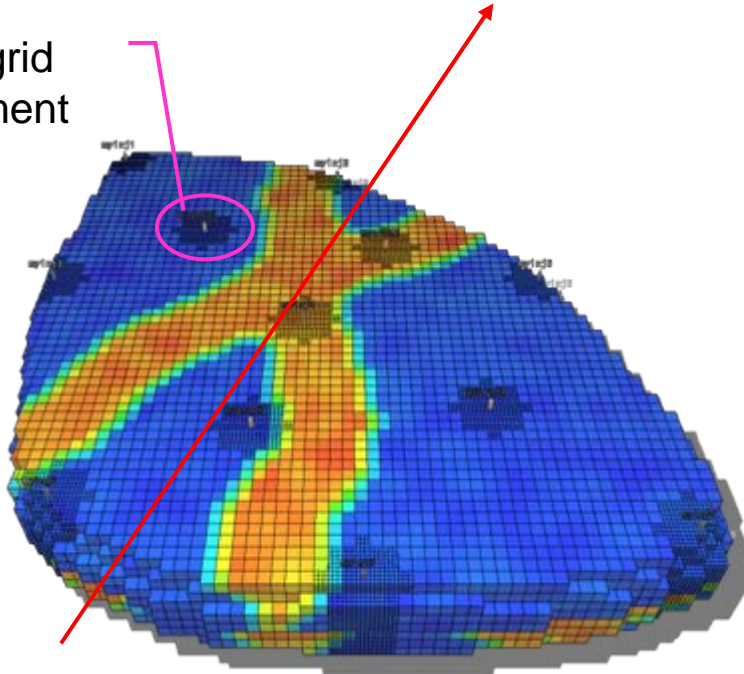
[Van Essen et al., CDC 2010]

# Two-level approach



# Example: 3D reservoir

local grid refinement

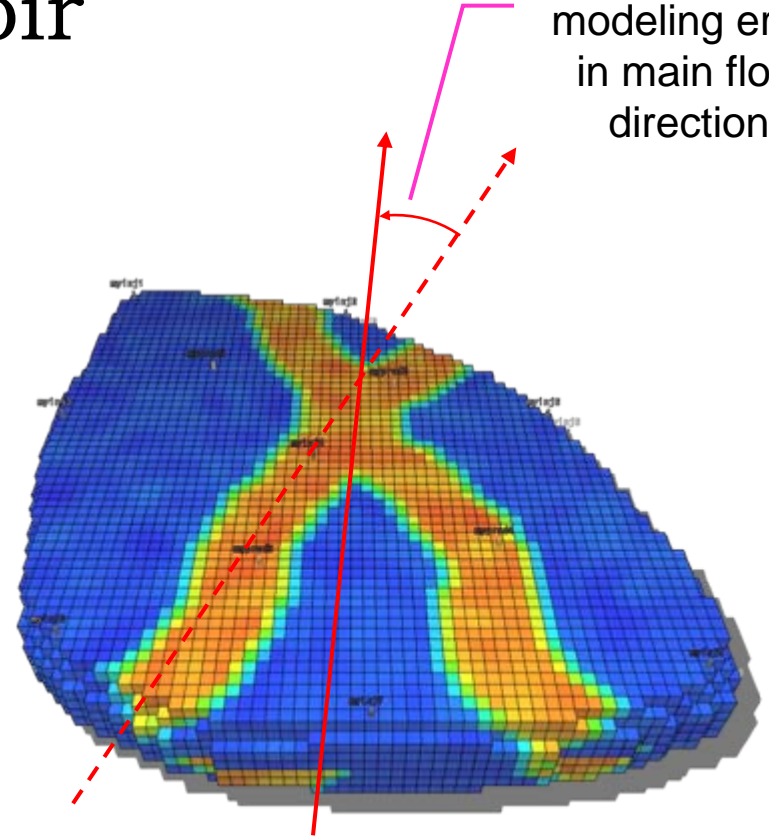


'truth' model

time step size: 0.25 days

8 injection wells, 4 production wells

modeling error in main flow direction



reservoir model

time step size: 30 days

Modeling error due to geological uncertainty & undermodeling of fast, local dynamics

# Example: 3D reservoir

3 production strategies

## 1. Reactive control

- Maximal injection rates/minimal bottom-hole pressures
- Shut-in wells when watercut  $>0.90$

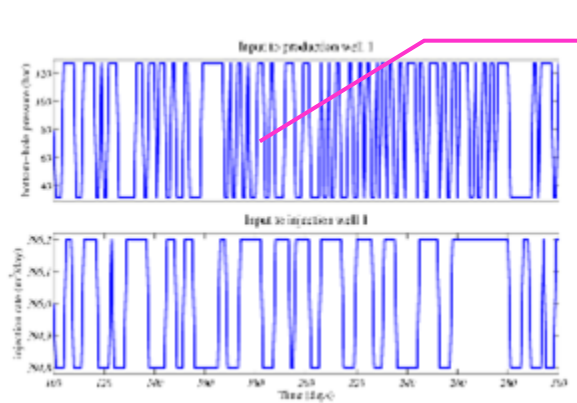
## 2. Open-loop life-cycle optimization

- Optimize inputs based on reservoir model
- Apply to 'truth' model

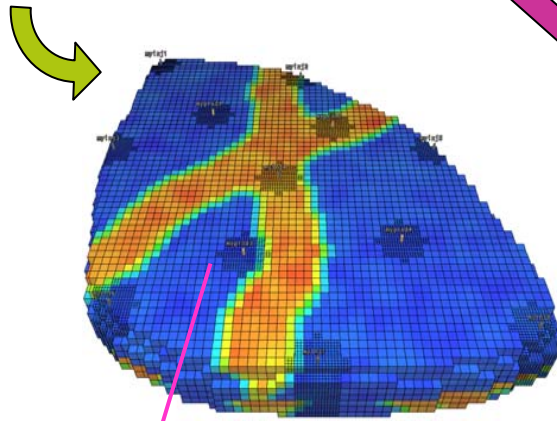
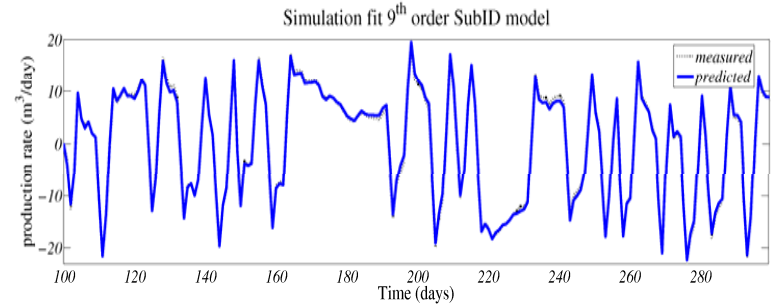
## 3. Combined dynamic optimization & MPC control

- Life-cycle optimization on reservoir model to obtain references
- Excitation on 'truth' model to identify low-order model
- MPC on 'truth' model to track references

# Low-order linear modeling (system id)



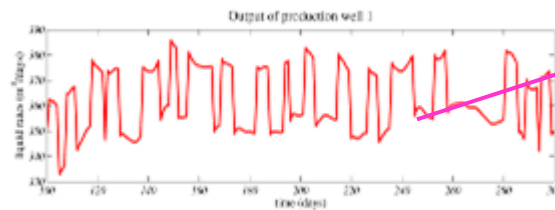
Persistently  
exciting inputs  
=  
Injection rates  
&  
Producer  
BHP's



Virtual  
asset

System  
Identification

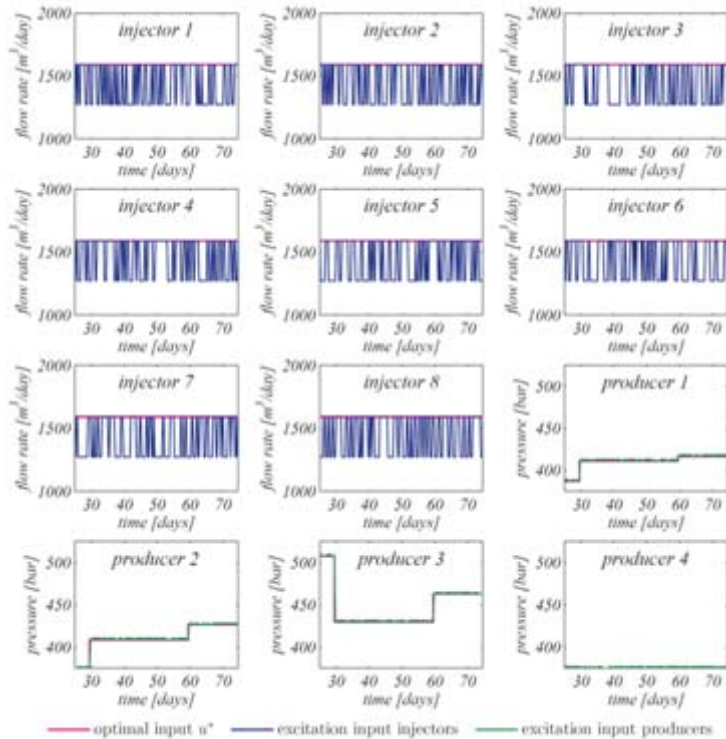
identified  
model



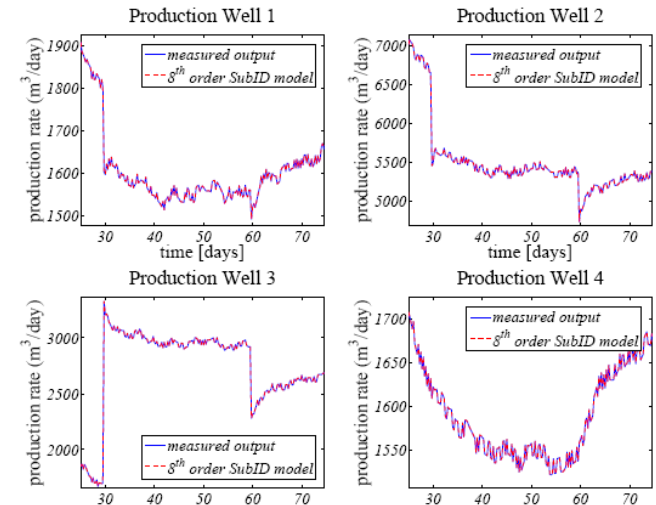
Liquid  
production flow  
rates

# Example: Identification Experiment

Input excitation for identification

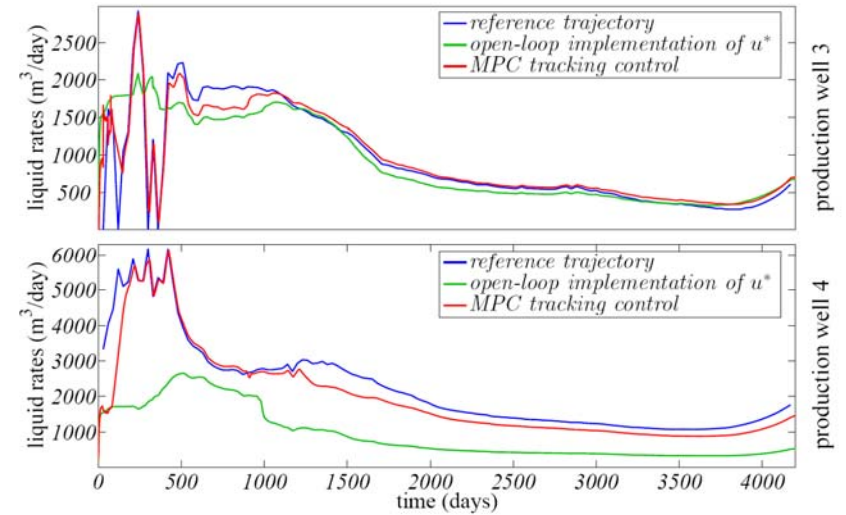
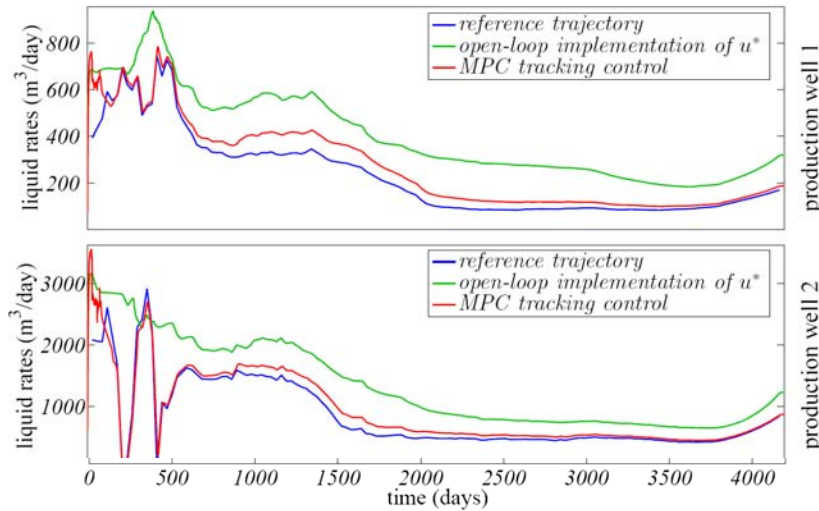


sub-space identification



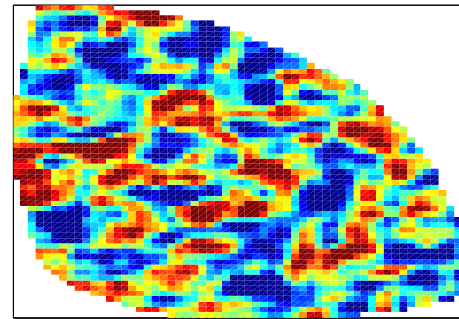
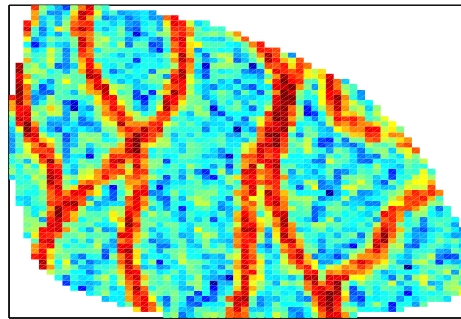
Simulation fit of 8<sup>th</sup> order identified model

# Example: Results



	<i>NPV</i>	<i>%</i>	
<i>Case 1: Reactive Control</i>	550 M\$	-	
<i>Case 2: Open-loop Optimization</i>	558 M\$	+1.5%	
<i>Case 3: Two-level Control</i>	594 M\$	+8.0%	
<i>Maximum based on reservoir model</i>	596 M\$	+8.4%	[Van Essen et al., CDC 2010]

# Control-relevant models



Why do such crude models  
sometimes work so well?

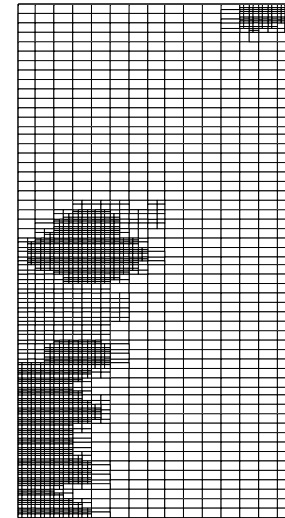
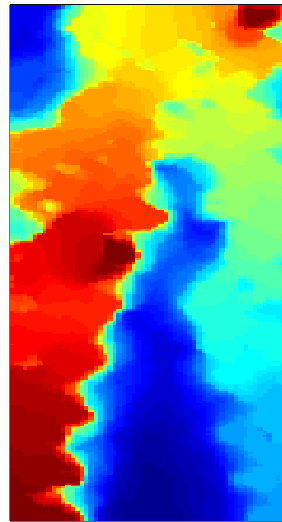
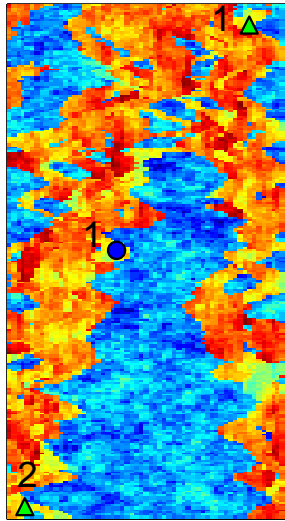
# Control-relevant models

Reservoir dynamics live in low-order space  
(much lower than the number of grid blocks)

- **Observation and control in the wells**
  - Models will typically be poorly observable and/or poorly controllable
  - Real (local) input-output dynamics is of limited order
- **Parameter estimation:**
  - Physical parameters (permeabilities) determine predictive quality but one parameter per grid block leads to excessive over-parametrization (not to be validated)

# Control-relevant models

- Opportunities for model reduction on the basis of (local) input-output maps



- one layer of SPE 10 model;  $0.0001 < k < 17000$  mD
- $60 \times 220 = 13200$  gridblocks
- Dominant nr. of Hankel singular values:  $O(100)$

[Vakili, 2010]

# Summary

- Challenging problems in model-based operation on the basis of highly uncertain information
- Size of the prize: .... field tests
- Key elements:
  - **Model-based optimization** under physical constraints and geological **uncertainties**
  - Appropriate merging of **physical and measured data** in **low-order** reliable and **goal-oriented models**
  - Capturing the essential **non-linear behaviour** of reservoirs
  - Challenging **parametrization** issues, in relation to control-relevance and **identifiability** (control-relevant geological models?)
  - **Learning** the optimal strategy in one shot (batch)

several papers and theses at [www.dcsc.tudelft.nl/~pvandenhof/publications.htm](http://www.dcsc.tudelft.nl/~pvandenhof/publications.htm)

# The Team:

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Sippe Douma



Jorn Van Doren



Remus Hanea



Ali Vakili

Thank you for your attention

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Keynote lecture,  
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Offshore Oil and Gas Production,  
31 May- 1 June 2012, Trondheim, Norway

