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# Risk Management in Oil Reservoir Water-Flooding under Economic Uncertainty

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TUD

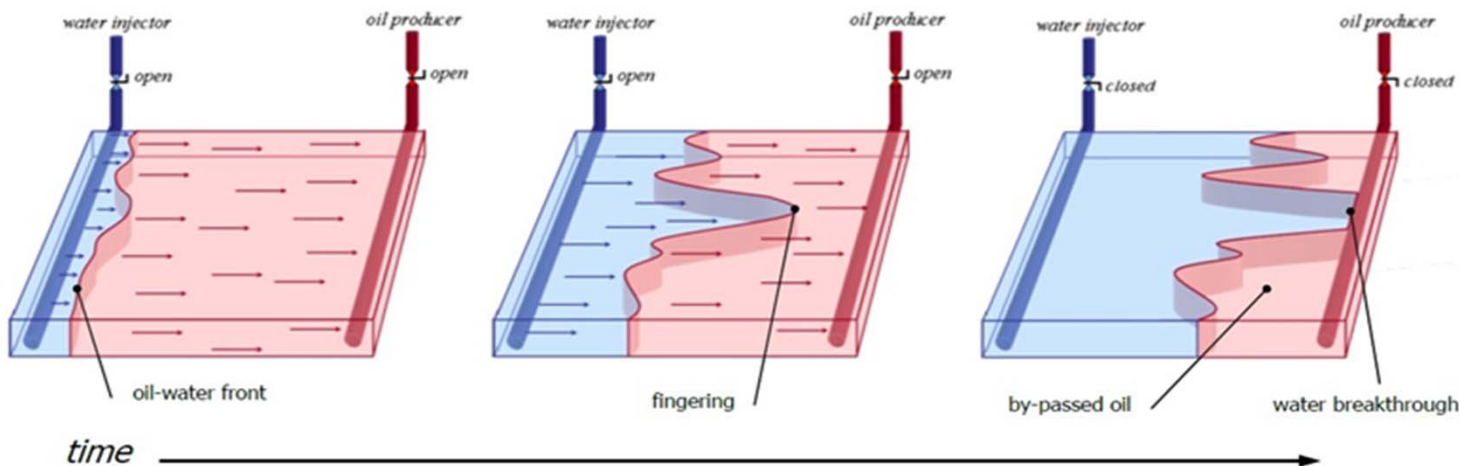
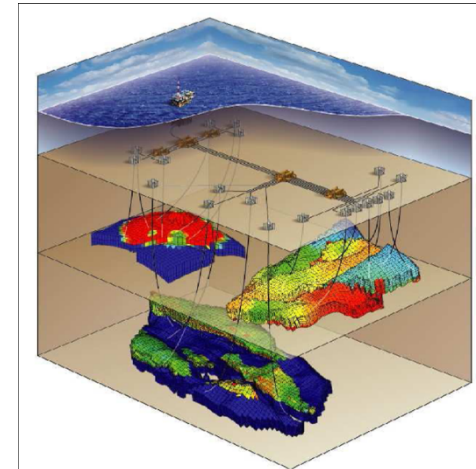


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Where innovation starts

# Oil Production

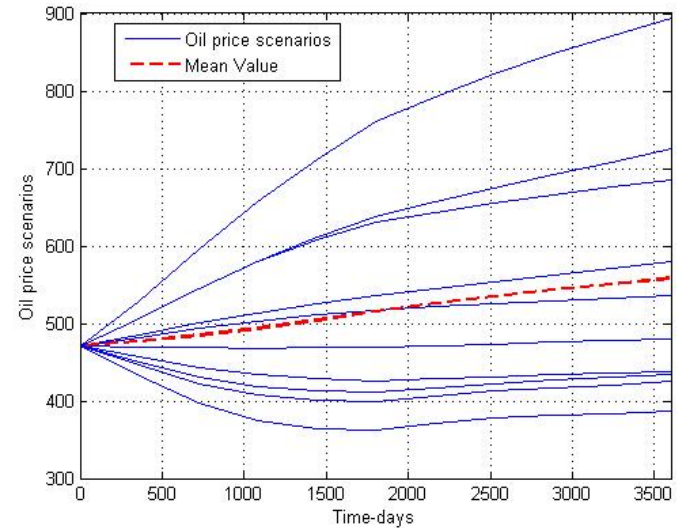
- Production from Oil reservoir
  - Porous rocks with oil in pores
  - $10^1$  to  $10^4$   $km^2$  in size
  - Geological structure heterogeneous
    - Very different rock properties within reservoir
  - Life cycle of 10 – 100 years
- Oil production phases
  - Primary production (5-15%)
  - Secondary production (Water-flooding)
  - Tertiary production



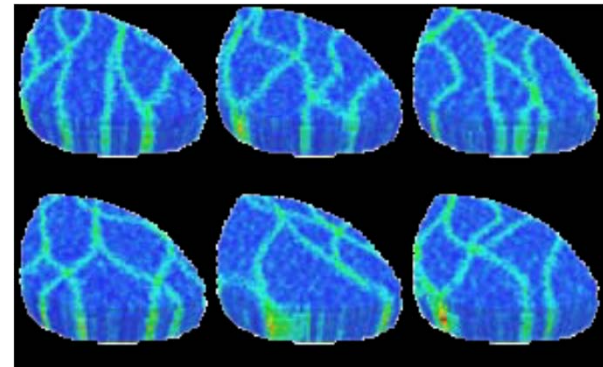
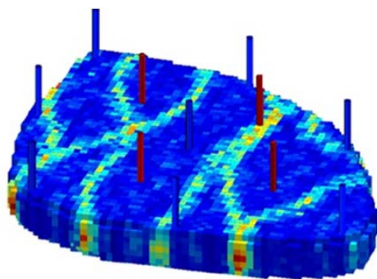
Van Essen et al. (2010)

# Challenges

- Large-scale, non-convex and non-linear optimization
- Uncertainty:
  - Economic uncertainty
    - Varying oil prices



- Parametric uncertainty



Decision making (model-based economic optimization) under **economic** uncertainty

# Contents

- Introduction
- **Model-based economic optimization and Reactive strategy**
- Handling risk of uncertainty
- Risk management
  - Worst-case optimization
  - Conditional Value-at-Risk (CVaR ) optimization
- Conclusions

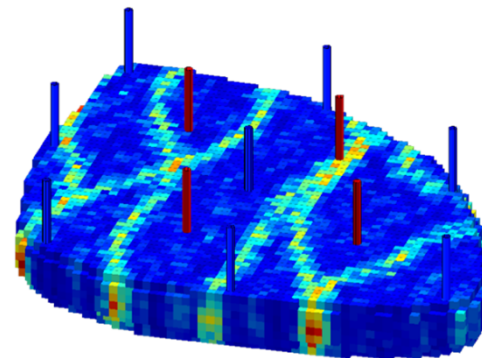
# Model-based optimization and Reactive strategy

- Net Present Value (**NPV**)

$$J_K(\mathbf{u}) = \sum_{k=1}^K \frac{\Delta t_k [r_o q_{o,k} - r_{wp} q_{wp,k} - r_{wi} q_{wi,k}]}{(1+b_\tau)^{\frac{t_k}{\tau}}}$$

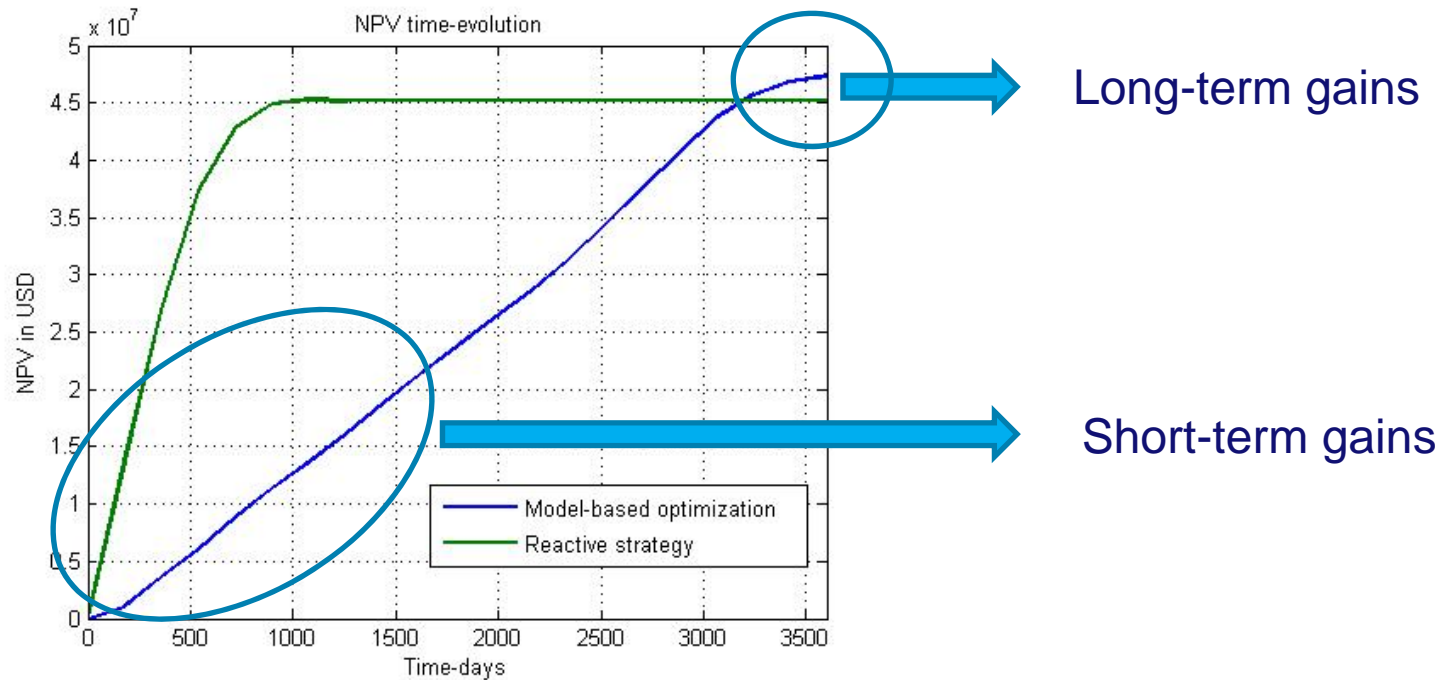
- Gradient obtained by solving an adjoint equation
- **Reactive strategy:**
  - Injection with maximum rates and shut-in production wells when it is no longer profitable.

- Experiment with the 'standard egg model'  
Jansen et al. (2014)



# Model-based optimization and Reactive strategy

Nominal model-based optimization and reactive strategy



It is desirable to include uncertainty in the model-based optimization

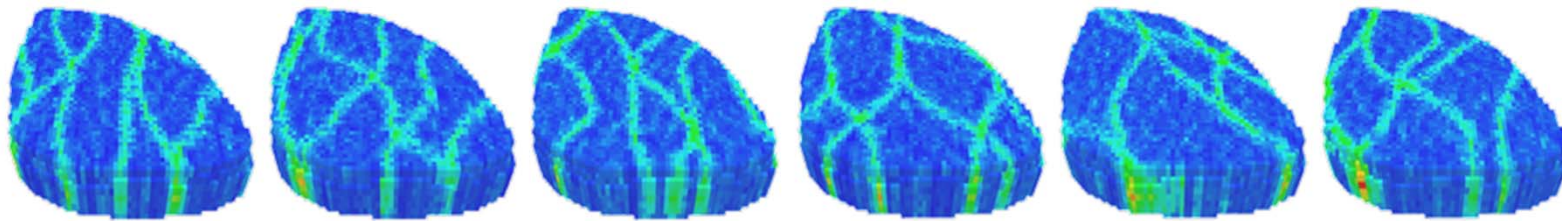
# Handling risk of uncertainties

## Literature Survey

Optimization over an ensemble of possible realizations (geological scenarios)

Van Essen, G., Zandvliet, M., Van den Hof, P. M. J., Bosgra, O., Jansen, J. D., 2009. Robust waterflooding optimization of multiple geological scenarios. SPE Journal 14 (01), 202–210, DOI: 10.2118/102913–PA.

An ensemble of 100 realizations of standard egg model:



The mean optimization  $J_{MO}$  for an ensemble of  $N_r = 100$  models

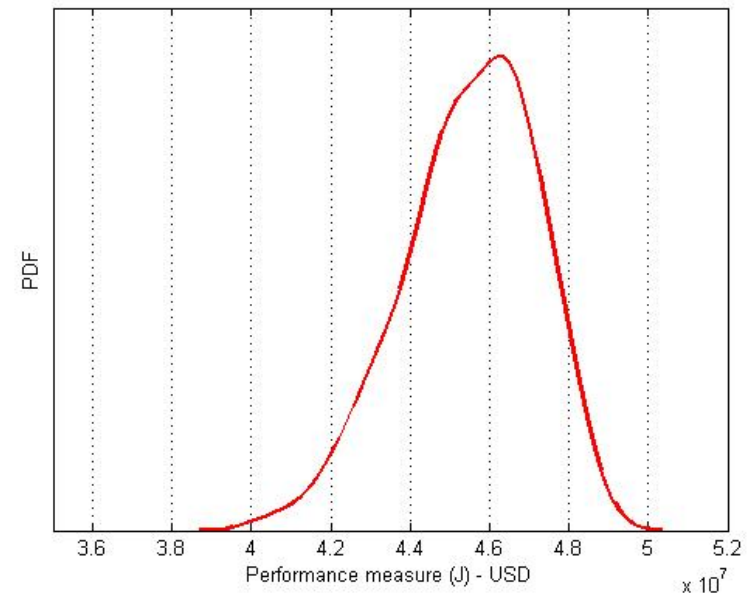
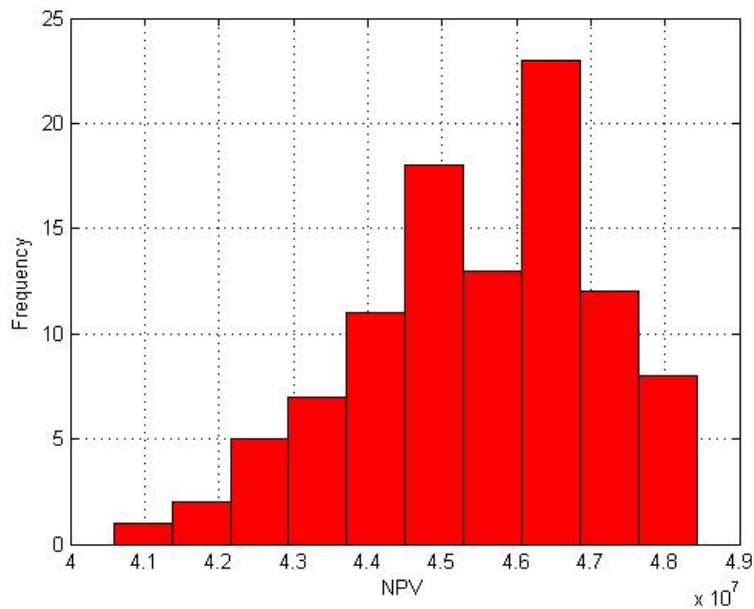
$$J_{MO} = \frac{1}{N_r} \sum_{i=1}^{N_r} J_i(u, \theta_i)$$

Where  $J$  is NPV,  $u$  is the control input and  $\theta_i$  is the uncertainty ensemble

# Handling risk of uncertainties

## Literature Survey

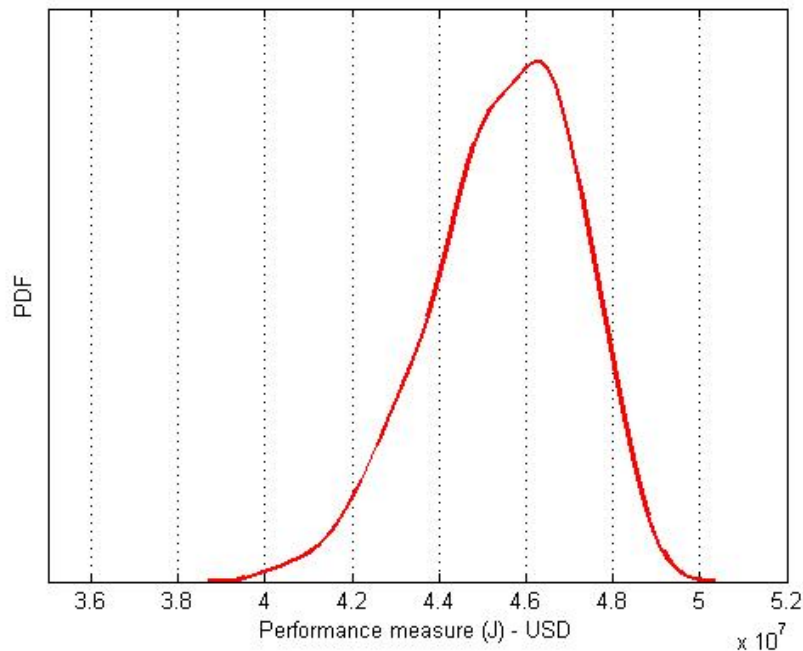
$$\max_u J_{MO} = \max_u \frac{1}{N_r} \sum_{i=1}^{N_r} J_i(u, \theta_i)$$



# Handling risk of uncertainties

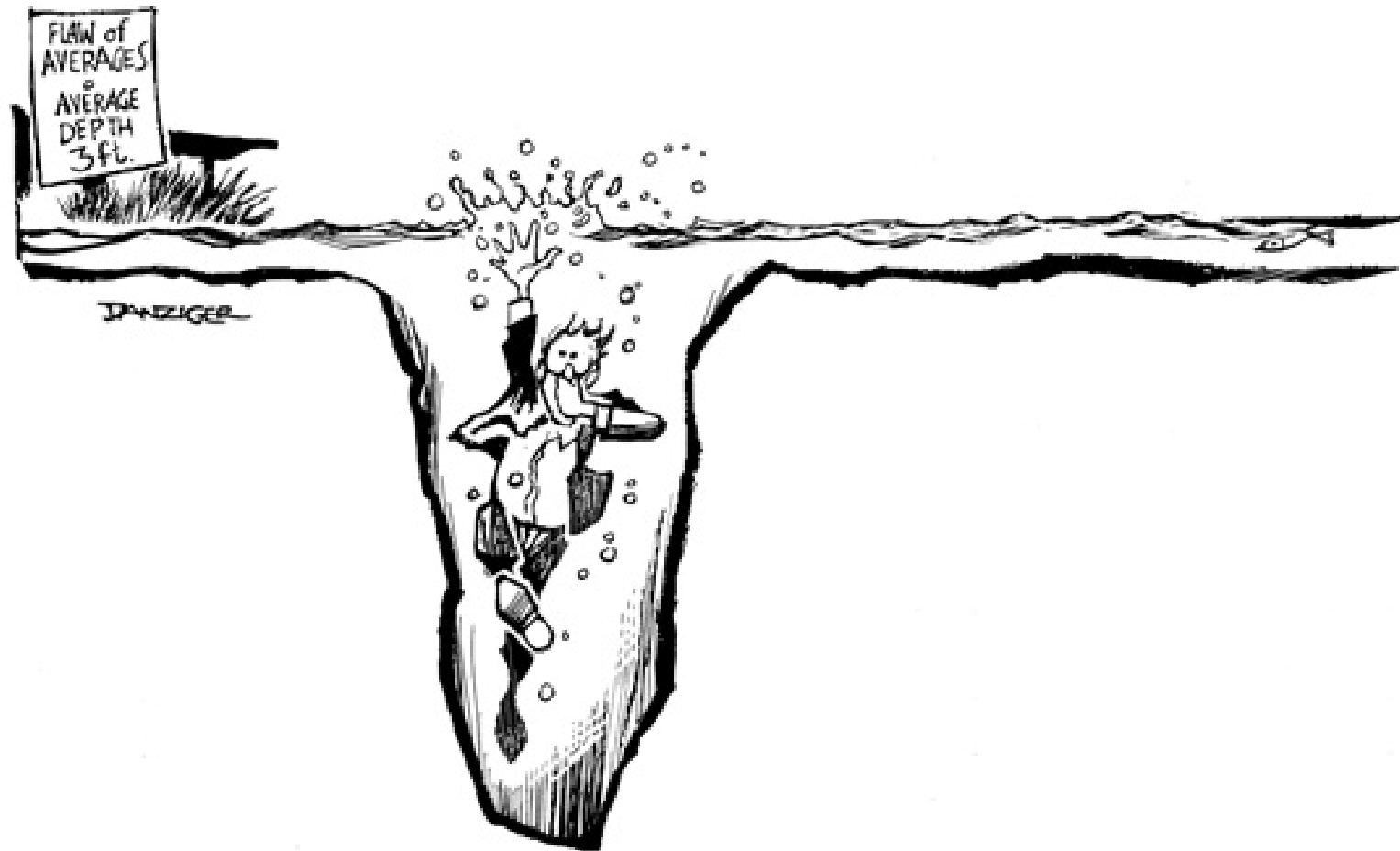
## Literature Survey

- Uncertainty is mapped to the distribution of the objective (NPV)
- Considers uncertainty in optimization framework, does not minimize the negative effect of it



Not a very robust scheme!

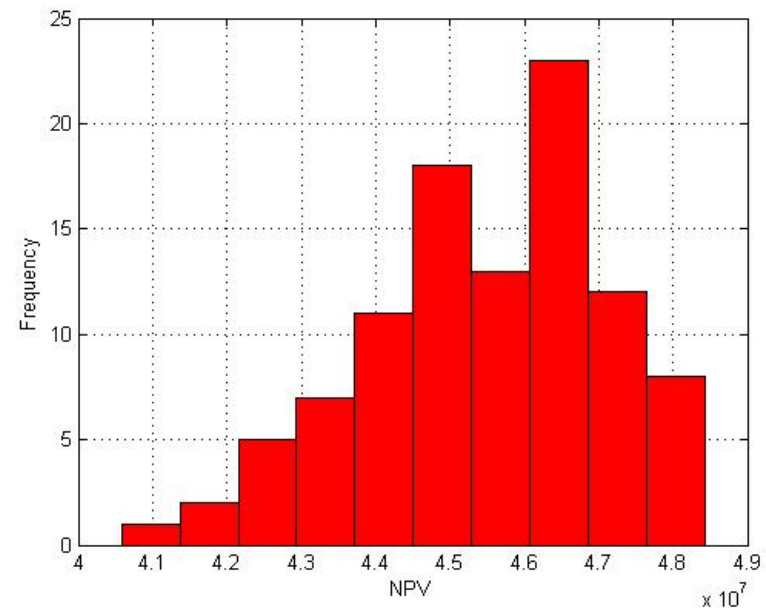
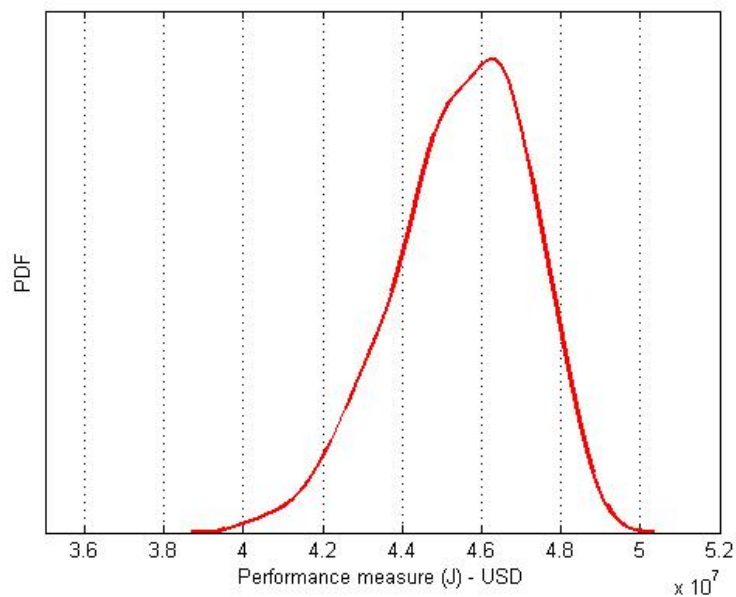
*“Flaw of averages”* (2009,2012), Sam Savage.



# Risk management

Risk is unpredicted variability or a potential loss of the expected economic objective.

Risk management is the shaping of gain\loss distribution.



# Risk management

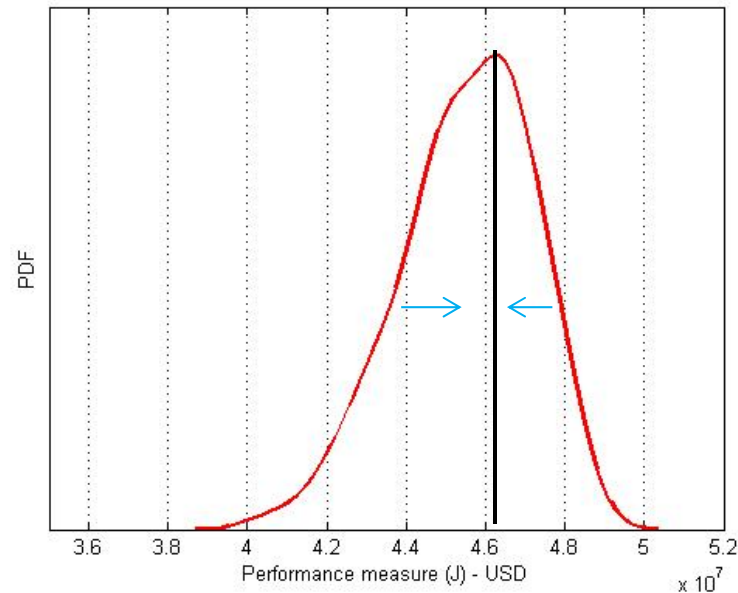
Risk measures H. Markowitz (1952), Rockafellar et. al (2000), Capolei et al. (2015b),

- Variance (Portfolio theory):

$$J_{MVO} = J_{MO} - \gamma J_V$$

$$J_{MO} = \frac{1}{N_r} \sum_{i=1}^{N_r} J_i(u, \theta_i) \quad (\text{Mean})$$

$$J_V = \frac{1}{N_r - 1} \sum_{i=1}^{N_r} (J_i(u, \theta_i) - J_{MO})^2 \quad (\text{Variance})$$



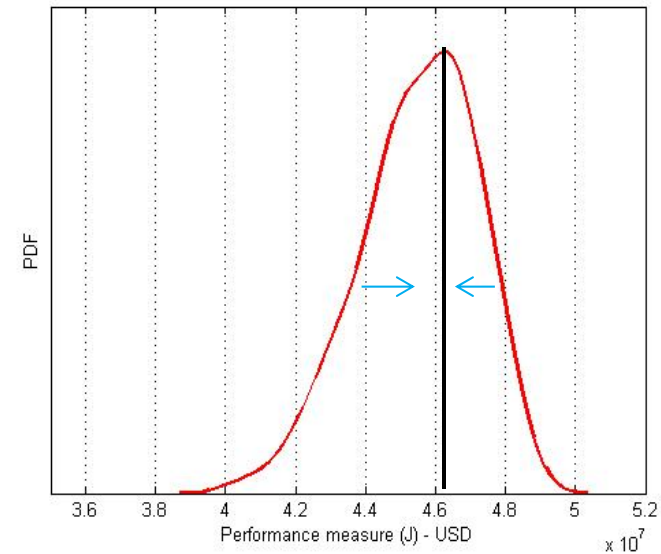
Capolei et al. (2015a),

Siraj et al. (2015)

# Risk management

## Risk measures

- Variance (Portfolio theory):
  - A symmetric measure of risk
  - It penalizes the best cases
  - The decision maker is mainly concerned with the worst cases



Using asymmetric risk measures to improve the worst cases without heavily compromising the best cases

# Risk management

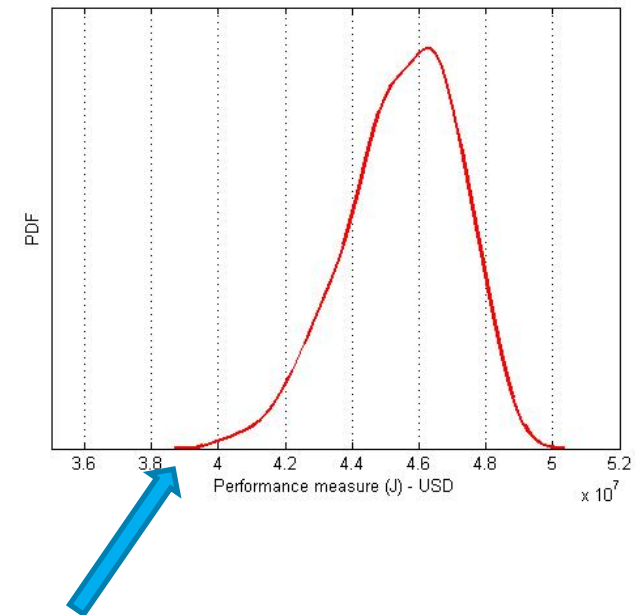
## Asymmetric Risk measures

Worst-case (Robust optimization):

$$\max_u \min_{\theta_i} J(u, \theta_i)$$

Reformulation:

$$\begin{aligned} & \max_u z \\ \text{s.t.} \quad & z \leq J(u, \theta_i) \quad \forall i \end{aligned}$$



# Risk management

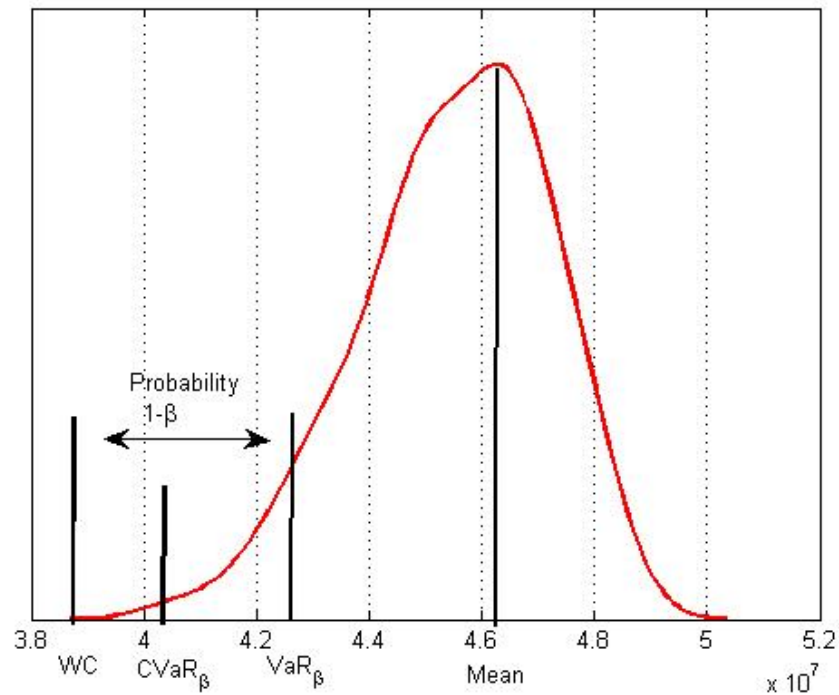
## Asymmetric Risk measures

Value at Risk (VaR):

$$VaR_{\beta}(X) = \min\{z \mid F_X(z) \leq \beta\}$$

Conditional Value at Risk (CVaR):

$$CVaR_{\beta}(X) = E[X \mid X \leq VaR_{\beta}]$$



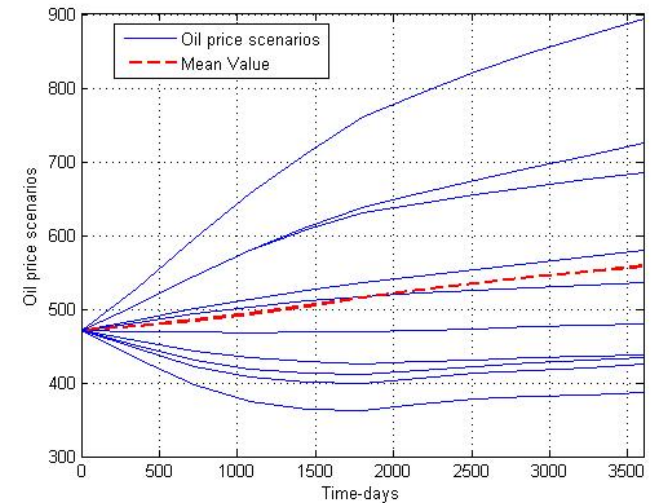
# Simulation experiments

Experiment details:

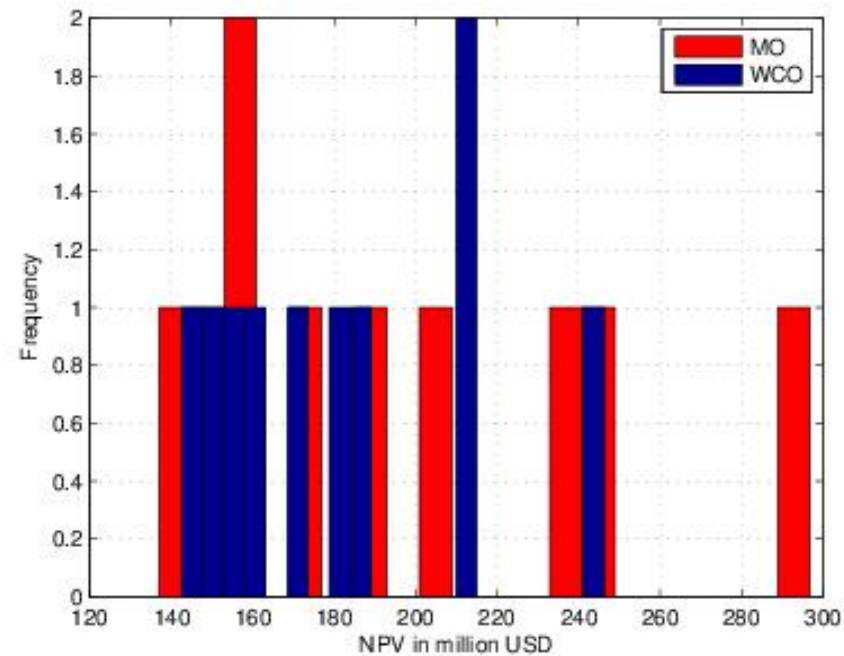
- An ensemble of oil price scenarios
- A single realization of reservoir egg model
- For worst-case optimization:

$$\begin{aligned} & \max_u z \\ \text{s.t.} \quad & z \leq J(u, \theta_i) \quad \forall i \end{aligned}$$

Where  $J$  is NPV,  $u$  is the control input and  $\theta_i$  is the uncertainty ensemble



# Worst-case robust optimization



Worst-case increase: 4.41%

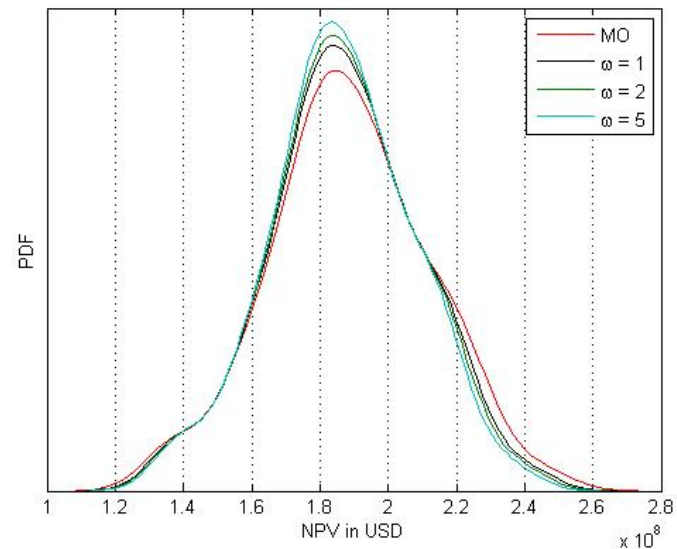
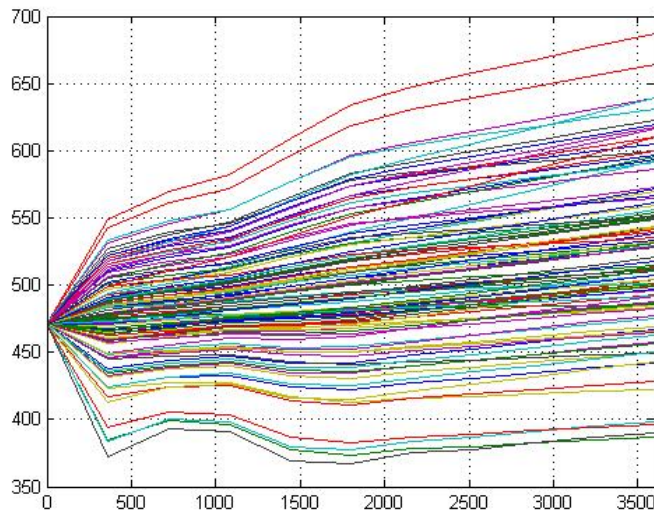
Average decrease: 6.18%

# Conditional value-at-Risk (CVaR) optimization

Handling economic uncertainty

$$\max_u J_M - \omega J_{CVaR}$$

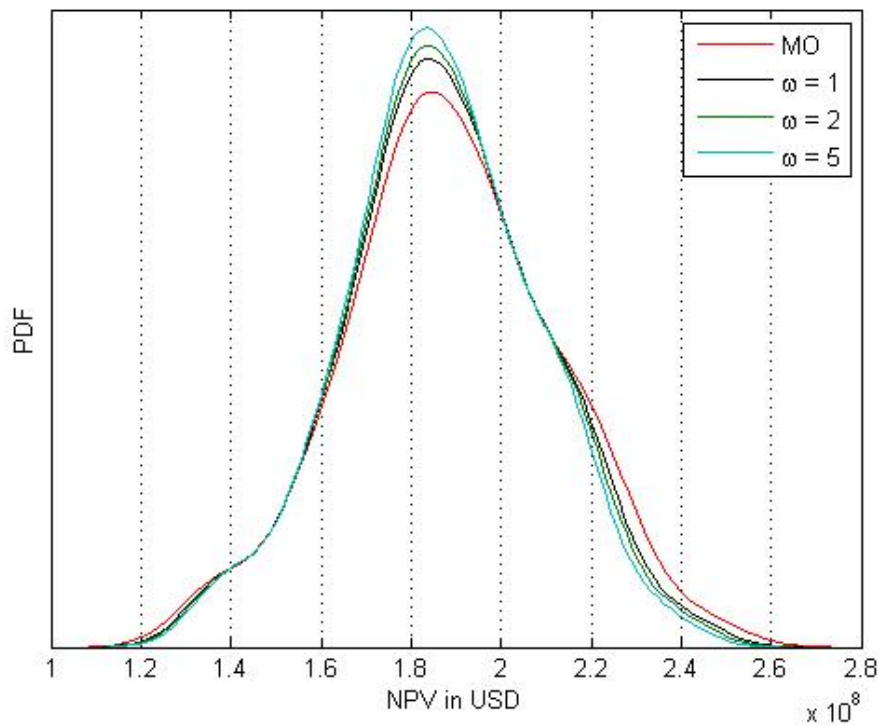
- $\beta = 0,8$



# Conditional value-at-Risk (CVaR) optimization

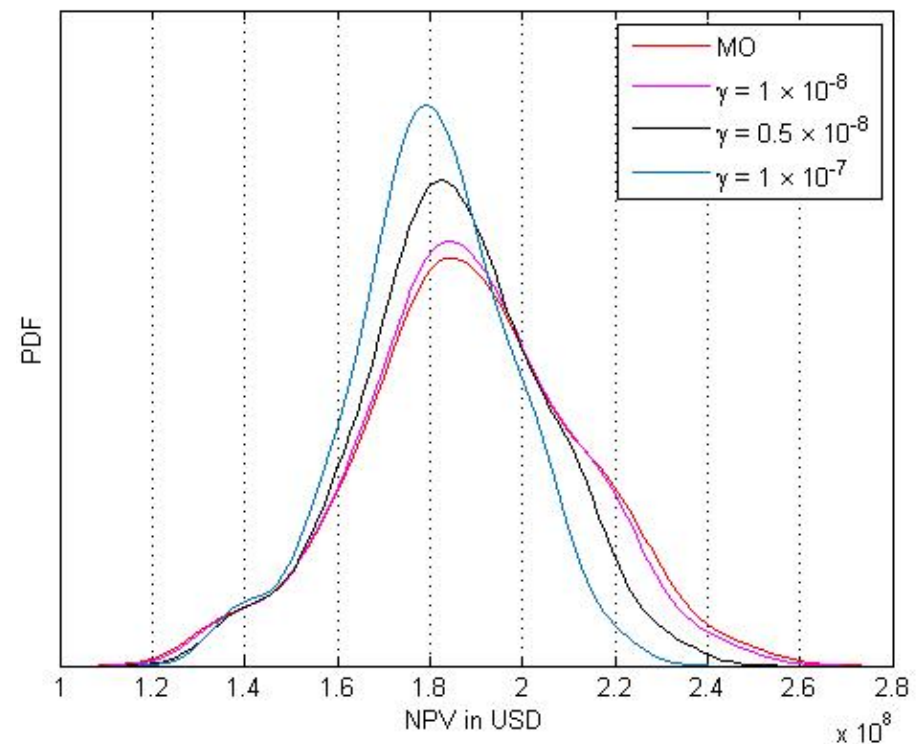
Mean - CVaR optimization

$$J_M - \omega J_{CVaR}$$



Mean - Variance optimization

$$J_M - \gamma J_V$$



# Take-home office messages

- Asymmetric risk management using concepts from the theory of risk
- Results highly dependent upon the chosen uncertainty quantification (uncertainty ensemble)
- CVaR and worst-case optimization provide improvement but at the cost of compromising best cases.

Future directions:

- Best cases can be retained by imposing some constraints.
- Semi-variance can be an attractive measure for asymmetric risk shaping (submitted to DYCOPS-CAB 2016)

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# Acknowledgments

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**Thank you**

ありがとうございます

arigatou gozaimas(u)

# Conditional Value at Risk (CVaR) [1]

Let  $X$  be a random variable with the cumulative distribution function  $F_X(z) = P\{X \leq z\}$ . The  $VaR$  of  $X$  with confidence level  $\beta \in ]0,1[$  is

$$VaR_\beta(X) = \min\{z \mid F_X(z) \geq \beta\}$$
$$CVaR_\beta(X) = E[X \mid X \geq VaR_\beta]$$

**CVaR optimization:**

$$CVaR_\beta(X) = \min_{\alpha} \left\{ \alpha + \frac{1}{1-\beta} E[X - \alpha]^+ \right\},$$

where

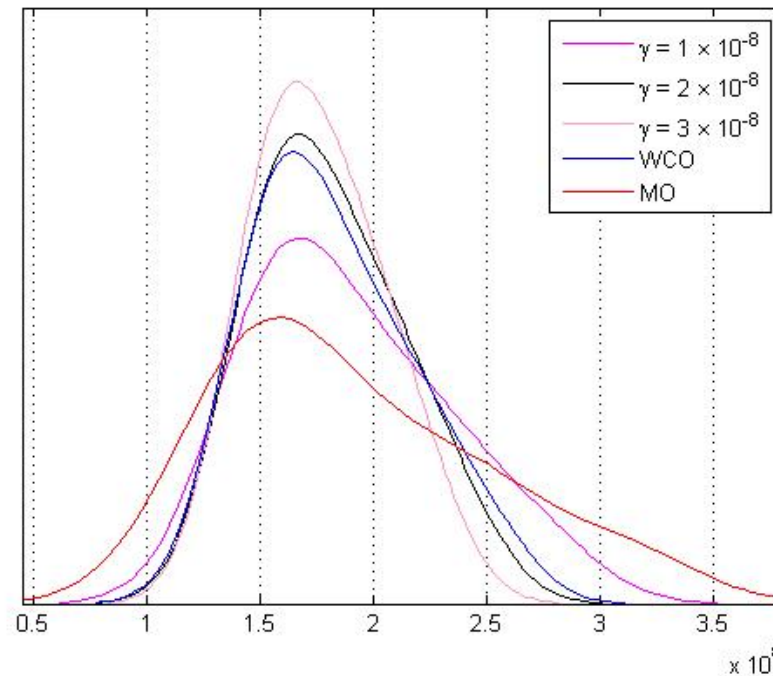
$$[t]^+ = \max\{t, 0\}$$

And

$$\min_X CVaR_\beta(X) = \min_{(X,\alpha)} \left\{ \alpha + \frac{1}{1-\beta} E[X - \alpha]^+ \right\},$$

# Worst-case robust optimization

$$J_{MWCO} = J_{MO} + \lambda J_{WCO}$$



# Optimization solver

## KNITRO

KNITRO:

A commercial solver for large-scale non-linear constraint optimization

Both interior-point (barrier) and active-set methods;

Programmatic interfaces: C/C++, Fortran, Java, Python;

Modeling language interfaces: AMPL ©, AIMMS ©, GAMS ©, MATLAB ©, MPL ©, Microsoft Excel Premium Solver ©;

The screenshot shows the website for Ziena Optimization LLC, which specializes in optimization software, modeling, and consulting. The page is titled "KNITRO Documentation" and provides information about user manuals, technical references, and support resources. The navigation menu includes links for PRODUCTS, SUPPORT, SERVICES, DISTRIBUTORS, COMPANY, and SITE MAP. The main content area is divided into several sections: "KNITRO 9.1 (PDF, HTML)", "Ziena License Manager (PDF)", "Older releases:" (listing KNITRO 9.0, 8.1, 8.0, and 7.0), "Discussion Forum" (a Google group for users), "TECHNICAL REFERENCES" (citing primary and interior point algorithm references), and "Supporting theory is given in:" (citing mathematical programming papers).

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**Discussion Forum** is at a Google group called "KNITRO". Anyone can view the discussions. To post a message you need to sign into Google, but Google accounts are free.

**TECHNICAL REFERENCES**

**The primary technical reference is:**  
R. H. Byrd, J. Nocedal, and R. A. Waltz, "KNITRO: An Integrated Package for Nonlinear Optimization" in *Large-Scale Nonlinear Optimization*, G. di Pillo and M. Roma, eds, pp. 35-59 (2006), Springer-Verlag. The *KNITRO User Manual* also contains a comprehensive list of technical references.

**The Interior Point algorithms are described in:**  
R. Byrd, M. E. Hillstorf, and J. Nocedal, "An Interior Point Method for Large Scale Nonlinear Programming" *SIAM J. Optimization*, 9,4, pp. 877-900 (1999).

**Supporting theory is given in:**  
R. Byrd, J.C. Gilbert, and J. Nocedal, "A Trust Region Method Based on Interior Point Techniques for Nonlinear Programming", *Mathematical Programming A*, 89: 149-185 (2000).  
R. Byrd, Guanghui Liu, and J. Nocedal, "On the Local Behavior of an Interior Point Method for Nonlinear Programming" in *Numerical Analysis*, D. F. Griffiths and D. J. Higham, eds, pp. 37-56 (1997), Addison Wesley Longman.

**KNITRO User Manual**  
Complete details for installing, using, and understanding Knitro.

**Ziena License Manager User's Manual**  
The manual for configuring and using Ziena licenses with KNITRO and AMPL.

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