Transmission Planning In A Restructured Environment

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* The views expressed in this presentation do not necessarily reflect those of ISO New England

Motivation

- The existing planning process lacks a clear and rigorous foundation
  - Involves ambiguous and conflicting assumptions
  - Includes inconsistent standards in different steps
- Our goal is to establish the foundation
  - To better understand the existing procedures
  - To explore ideas/approaches addressing new challenges
- As part of the effort, we explore four transmission planning models in the following

Transmission Planning In a Vertically Integrated Environment (Overview)

- Coordinated with the generation expansion plan
- Least cost planning subject to reliability criteria
  - E.g., N-1 contingency criteria
- Uncertain parameters
  - E.g., load
- Deterministic power flow study under various scenarios
  - e.g., 90/10 load

Transmission Planning In a Restructured Environment

- No “co-optimization” with generation planning
- Least cost planning with constraints
- Increasing number of uncertainties
  - Load
  - Variable resources, e.g., wind
  - New generation capacity location and size
- Deterministic power flow study under various scenarios
  - The number of scenarios increases exponentially

In This Presentation

- Challenges in a restructured environment
- *Different approaches to deal with uncertainty*
  - “Most-likelihood” model
  - “Worst-case” model
  - Robust optimization model
  - Chance-constrained model
- An illustrative example
- Conclusion

A Simplified Transmission Planning Problem

$$\underset{u_{ij}\in\{0,1\}}{Min} \quad \sum_{(i,j)\in\Omega} u_{ij} C_{ij},$$

$$s.t. \quad p_i + \underline{p_i^W} - \underline{d_i} = \sum_{j\in N_i} f_{ij},$$

$$p_i \le \underline{c_i},$$

$$f_{ij} = (b_{ij,0} + u_{ij} b_{ij})\ \theta_i - \theta_j \quad ,$$

$$f_{ij} \le f_{ij\,\max,0} + u_{ij}\, f_{ij\,\max}$$

u_{ij} : Expansion decision
Ω : Available paths
C_{ij} : Cost of path (i, j)
p_i, $\underline{p_i^W}$: Generation
$\underline{d_i}$: Load
$\underline{c_i}$: Generation capacity
θ_i : Bus angle
$b_{ij,0}$, b_{ij} : Line susceptance
$f_{ij\,max,0}$, $f_{ij\,max}$: Flow limit

- How to handle uncertainty in {$\underline{d_i}$, $\underline{p_i^W}$, $\underline{c_i}$} ?
  - More of a modeling issue than a solution issue

Model I: Most-likelihood Scenario

- Replace {$\underline{d}_i$, $\underline{p}_i^W$, $\underline{c}_i$} by their most likely realization

$$\underset{u_{ij}\in\{0,1\}}{Min} \quad \sum_{(i,j)\in\Omega} u_{ij} C_{ij},$$

$$s.t. \quad p_i + \boxed{\overline{p}_i^W} - \boxed{\overline{d}_i} = \sum_{j\in N_i} f_{ij},$$

$$p_i \le \boxed{\overline{c}_i},$$

$$f_{ij} = (b_{ij,0} + u_{ij} b_{ij})\ \theta_i - \theta_j \quad ,$$

$$f_{ij} \le f_{ij\max,0} + u_{ij} f_{ij\max}$$

Deterministic

Model I: Most-likelihood Scenario

- The non-linear constraints can be reformulated as linear ones, i.e.,

$$f_{ij} = (b_{ij,0} + u_{ij} b_{ij}) \ \theta_i - \theta_j \quad \Longleftrightarrow \quad \boxed{\begin{aligned} & f_{ij} = f_{ij,0} + y_{ij}, \\ & f_{ij,0} = b_{ij,0} \ \theta_i - \theta_j \ , \\ & y_{ij} \le b_{ij} \ \theta_i - \theta_j \ + (1 - u_{ij}) M, \\ & y_{ij} \ge b_{ij} \ \theta_i - \theta_j \ - (1 - u_{ij}) M, \\ & -u_{ij} M \le y_{ij} \le u_{ij} M \end{aligned}}$$

Resulting in a MILP

Model I: Most-likelihood Scenario

- Pros
  - The deterministic model can be solved by mature software

- Cons
  - Requires the likelihood knowledge of uncertain parameters, which may not be available
  - May end up with violation of reliability constraints – Risky!

To be conservative?

Model II: Worst-case Scenario

- Replace {$\underline{d}_i$, $\underline{p}_i^W$, $\underline{c}_i$} by their worst possible realization

$$\min_{u_{ij}\in\{0,1\}} \sum_{(i,j)\in\Omega} u_{ij} C_{ij},$$

$$s.t. \quad p_i + \boxed{p_i^{W*}} - \boxed{d_i^*} = \sum_{j\in N_i} f_{ij},$$

$$p_i \le \boxed{c_i^*},$$

$$f_{ij} = (b_{ij,0} + u_{ij} b_{ij})\ \theta_i - \theta_j \quad ,$$

$$f_{ij} \le f_{ij\max,0} + u_{ij} f_{ij\max}$$

Deterministic

Model II: Worst-case Scenario

- This model represents the current planning process, with the “worst” case identified through stressing the system in various ways

- Pros
  - Deterministic, no need for probability distribution

- Cons
  - A large number of scenarios need to be studied, which could be a non-trivial task <u>A systematic way?</u>

Model III: Robust Optimization

- Consider $\{\underline{d}_i, \underline{p}_i^W, \underline{c}_i\}$ for all possible realizations

$$\underset{u_{ij}\in\{0,1\}}{Min} \quad \sum_{(i,j)\in\Omega} u_{ij} C_{ij},$$

$$s.t. \quad p_i + p_i^W - d_i = \sum_{j\in N_i} f_{ij}, \quad \boxed{\forall p_i^W \in \Omega_{p_i^W},\ \forall d_i \in \Omega_{d_i}},$$

$$p_i \le c_i, \quad \boxed{\forall c_i \in \Omega_{c_i}},$$

$$f_{ij} = (b_{ij,0} + u_{ij} b_{ij})\ \theta_i - \theta_j \ ,$$

$$f_{ij} \le f_{ij\max,0} + u_{ij} f_{ij\max}$$

"Robust feasible"

Model III: Robust Optimization

- Robust counterpart

$$p_i + p_i^W - d_i = \sum_{j \in N_i} f_{ij}, \quad \forall p_i^W \in \Omega_{p_i^W}, \forall d_i \in \Omega_{d_i},$$

$$p_i \le c_i, \quad \forall c_i \in \Omega_{c_i}$$

$$\Updownarrow$$

$$\sum_{j \in N_i} f_{ij} \le c_i^{Lo} + p_i^{W\,Lo} - d_i^{Up}$$

Deterministic

  – In this simplified problem: uncertain parameters are independent; linear DC flow is used

Model III: Robust Optimization

- Can replace the study of various scenarios in current practice

- Pros
  - Can be converted to a computationally tractable deterministic problem under certain conditions
  - Need only range, not distribution of uncertain parameters
  - "Uncertainty immunized" within the uncertain range

- Cons
  - Too conservative!

Model IV: Chance-constrained Optimization

- Specify a risk level α of constraint violation

$$\underset{u_{ij}\in\{0,1\}}{Min} \quad \sum_{(i,j)\in\Omega} u_{ij} C_{ij},$$

$$s.t. \quad \Pr\left[\begin{array}{l} p_i + \overline{p}_i^{W} - \overline{d}_i = \sum_{j\in N_i} f_{ij}, \\ p_i \le \overline{c}_i, \\ f_{ij} = (b_{ij,0} + u_{ij} b_{ij})\ \theta_i - \theta_j\ , \\ f_{ij} \le f_{ij\max,0} + u_{ij} f_{ij\max} \end{array}\right] \ge 1 - \boxed{\alpha}$$

Model IV: Chance-constrained Optimization

- Pros
  - Intuitive
  - Allows explicit risk control

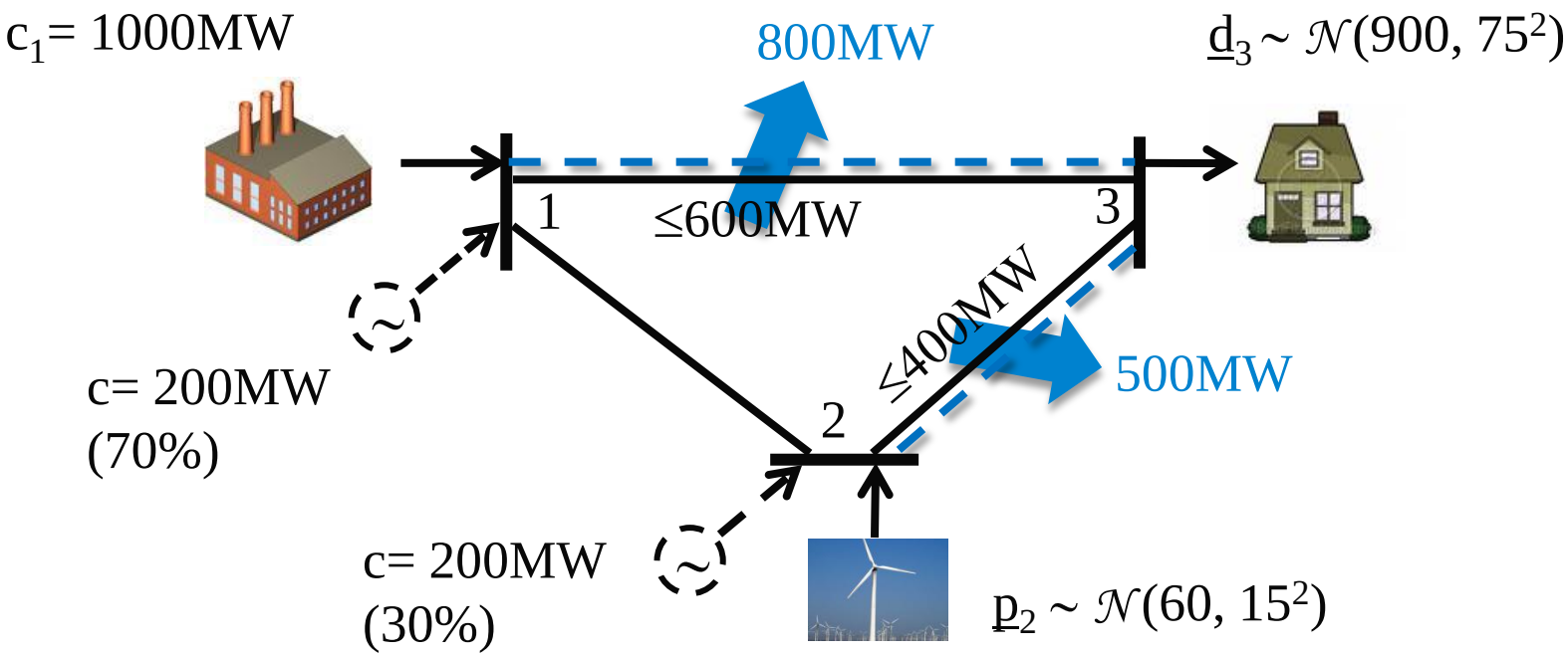
- Cons
  - Requires probability distribution of uncertain parameters
  - Difficult to solve

Summary of Four Models

	Most Likelihood	*Worst Case / Robust optim.*	*Chance-Constrained*
Risk	High	**Low**	**Controllable**
Cost	Low	High	Risk-associated
Information	Moderate	Low	High
Computation	Low	**Intense / Could be challenging**	**Challenging**

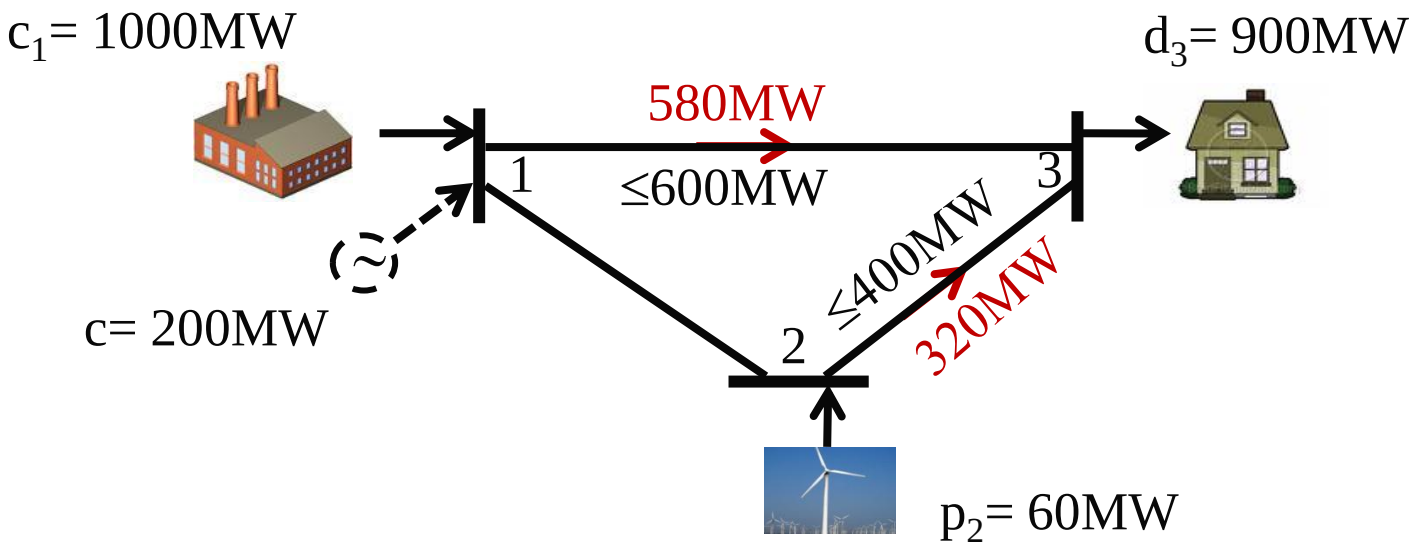
An Illustrative Example

- 3-bus system with two available transmission upgrades with cost C_{13}= \$5×10^6, C_{23}= \$3×10^6



Solution of Most-likelihood Model I

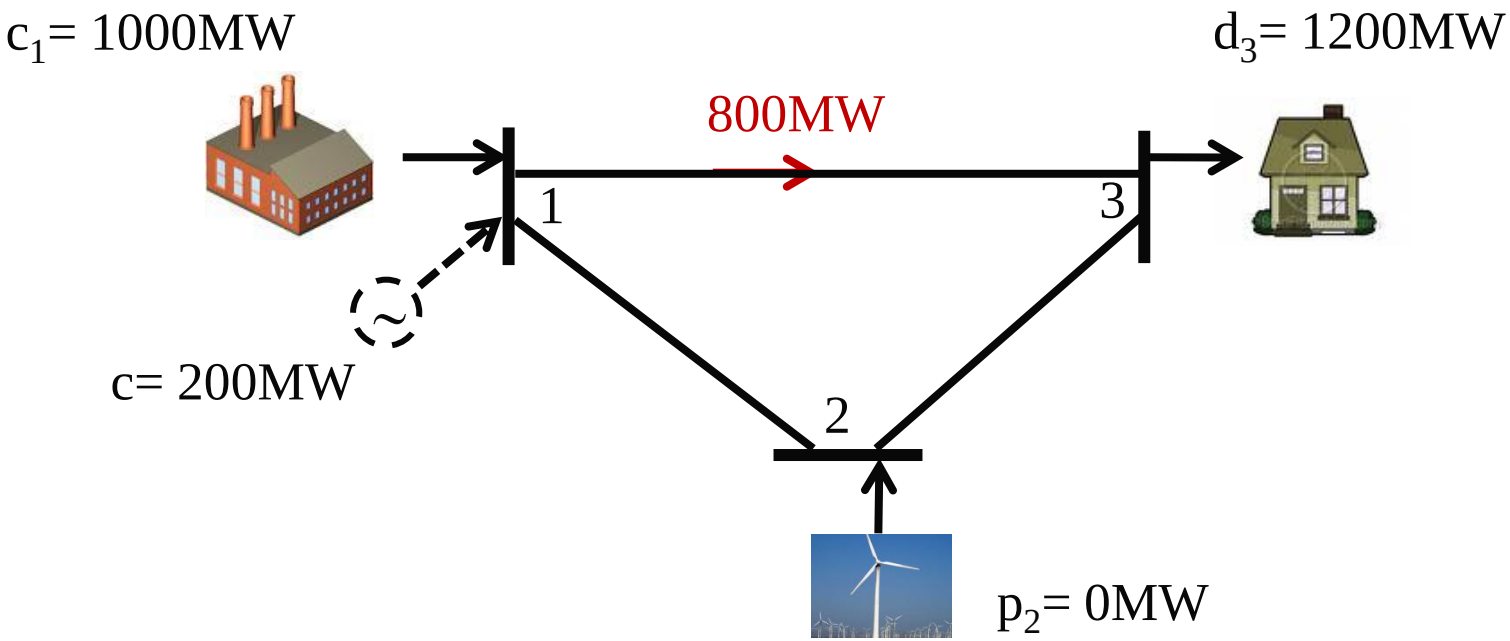
- Most likely scenario: d_3=900, p_2=60, c=200 at bus 1



  - No transmission upgrade needed⇒ u_{13}=u_{23} =0, cost= 0
  - Pr(constraint violation) > Pr(line13 violation, new capacity at node1) = Pr($(2\underline{d}_3 - \underline{p}_2)/3 > 600$) × 0.7 = 0.242 (high!)

Solution of Worst-case Model II

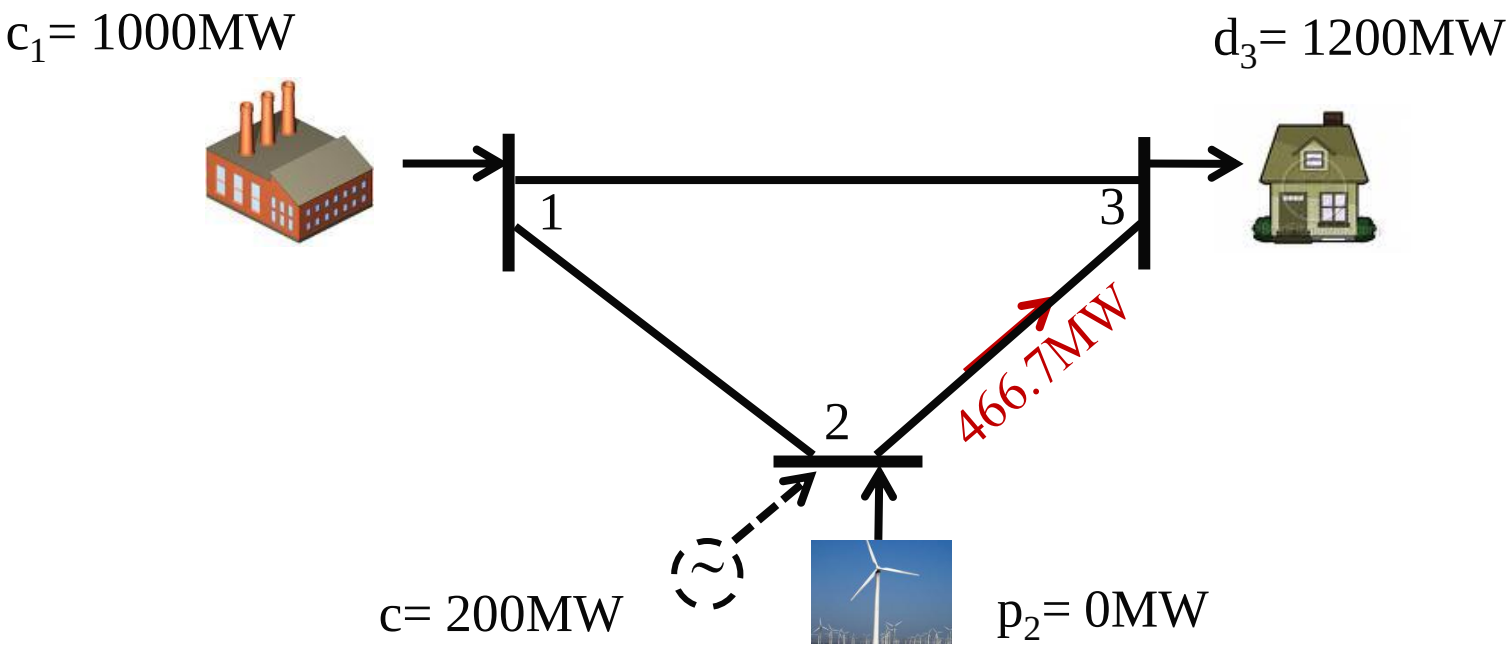
- Assume the range [μ-4σ, μ+4σ] for normal dist. $\mathcal{N}(\mu; \sigma^2)$
- Worst-case for line 1-3: d_3=1200, p_2=0, c=200 at bus 1



  – Power flow on line 13 is 800MW > 600MW $\Rightarrow$ u_{13} = 1

Solution of Worst-case Model II

- Worst-case for line 2-3: d_3=1200, p_2=0, c=200 at bus 2



  – Power flow on line 23 is 466.7MW > 400MW $\Rightarrow$ u_{23} = 1

Solution of Worst-case Model II

- Obtain two worst scenarios by stressing different constraints

- Both transmission upgrades are needed ($u_{13}=u_{23}=1$)
  - Cost= $\$8\times10^6$, no risk of constraint violation

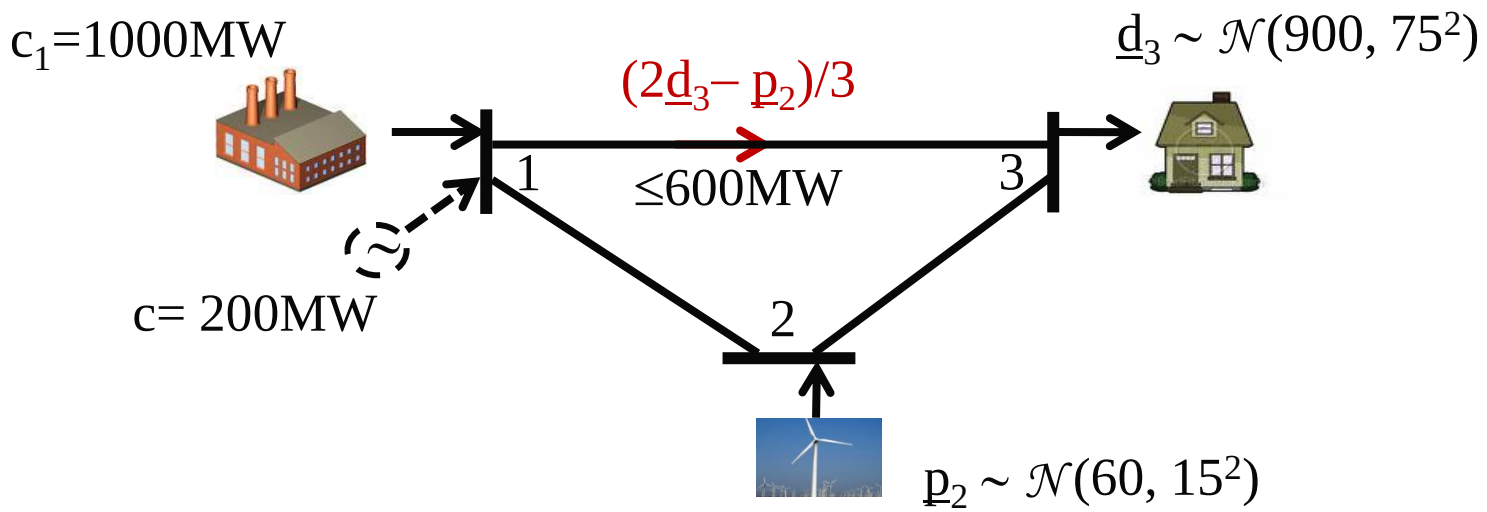
Solution of Robust-optimization Model III

- The same solution as the worst-case model II
  - In this simple example, no “worst case” is missed

- Both transmission upgrades are needed ($u_{13}=u_{23}=1$)
  - Cost= $\$8\times10^6$, no risk of constraint violation

Solution of Chance-constrained Model IV

- Criterion: Probability of constraint violation ≤ 0.1% (α)
- Consider first the violation of flow limit on line 13
  - Scenario 1: new capacity 200MW at node 1 (Prob = 0.7)



  - Pr(line13 violation | scenario 1) = Pr($(2\underline{d}_3 - \underline{p}_2)/3 > 600$) = 0.345

Solution of Chance-constrained Model IV

- Similarly, Pr(line13 violation | scenario 2) = 0.042
- Pr(line13 violation) = $0.345 \times 0.7 + 0.042 \times 0.3 = 0.254$
- Pr(constraint violation) $\geq$ Pr(line13 violation) > α
- Line 13 has to be upgraded $\Rightarrow$ $u_{13} = 1$, $f'_{13\,max} = 800$MW

- Now consider the violation of flow limit on line 23
  - The 800MW line 13 new limit will never be violated
  - Similar to the above calculation, Pr(line23 violation) = 0.00062
  - Pr(constraint violation) = Pr(line23 violation) < 0.001(α) <u>OK!</u>
  - Line 23 needs no upgrading $\Rightarrow$ $u_{23} = 0$

Comparison of Four Models

	Most Likelihood	Worst Case / Robust Optim.	Chance-Constrained
Solution	No upgrade	Upgrade line 1-3, line 2-3	Upgrade line 1-3
Cost	\$0	$\$8\times10^6$	$\$5\times10^6$
Prob. of constr. violation	> 0.242	0	0.062% ($<\alpha$)

Conclusion

- Transmission planning faces an increasingly uncertain environment, demanding new model & solution technologies
- The worst-case model represents the current planning practice; Robust Optimization can be used to improve the current practice by systematically identifying the worst cases
- The Chance-constrained model allows explicit control of the risk level, leading to a risk-based planning paradigm
- Next step includes: tractable solutions to RO and CP