Economic Dispatch with Sub-hourly Simulation

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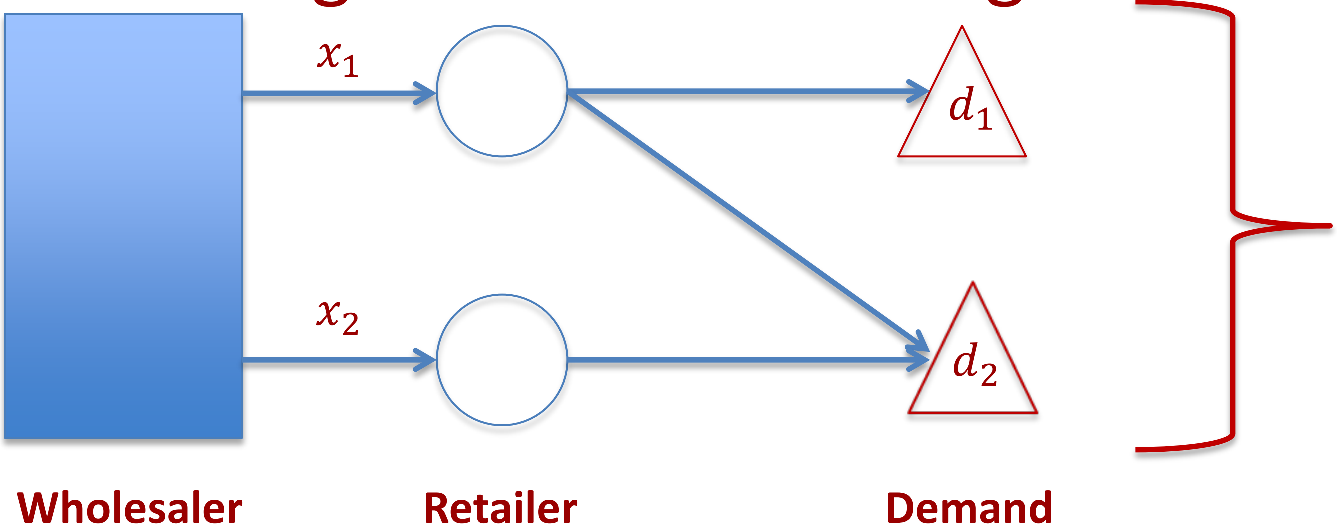
The Agenda

- **Stochastic Programming Technology**
  - Uncertainty Quantification (UQ) for Operations
  - Quick Demo
  - UQ Engines (SAA and SD)
- **Economic Dispatch with Simulation**
  - Economic Dispatch Model
  - Wind Simulation
  - Stochastic Decomposition and Economic Dispatch Setting
- **Results with Hourly and Sub-hourly Simulation**
  - Illinois Network Data
  - Hourly v Sub-hourly Ramping
  - UQ using SAA (Extensive Formulation) and SD
- **Conclusions**
  - Main Take Away
  - Other On-Going Work

UQ for Operations

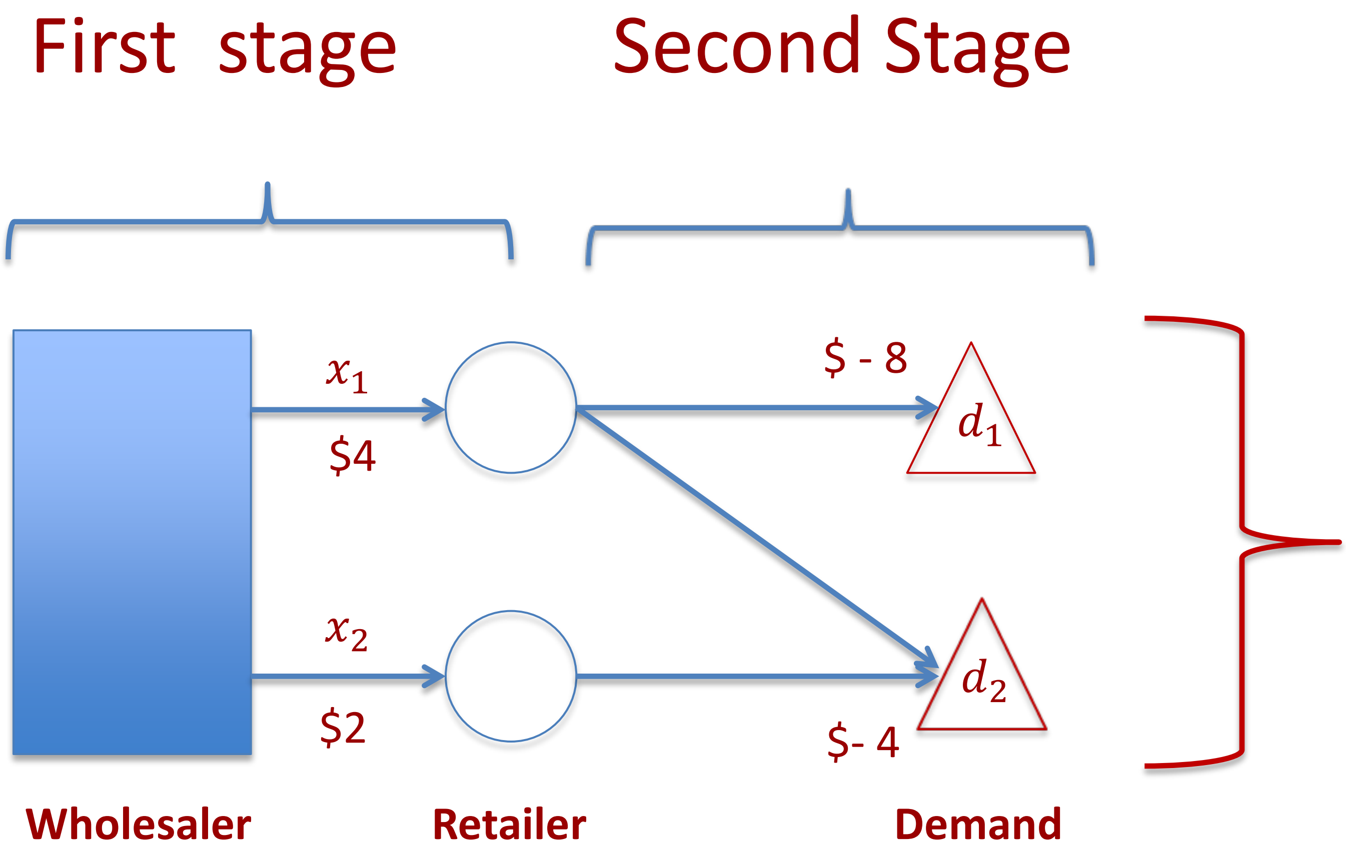
- Two products serve two types of demands:
- x_j are order quantities to be determined. But,

First stage   Second Stage



Demands are normally distributed with mean = 100 and std. dev = 12.5

UQ for Operations

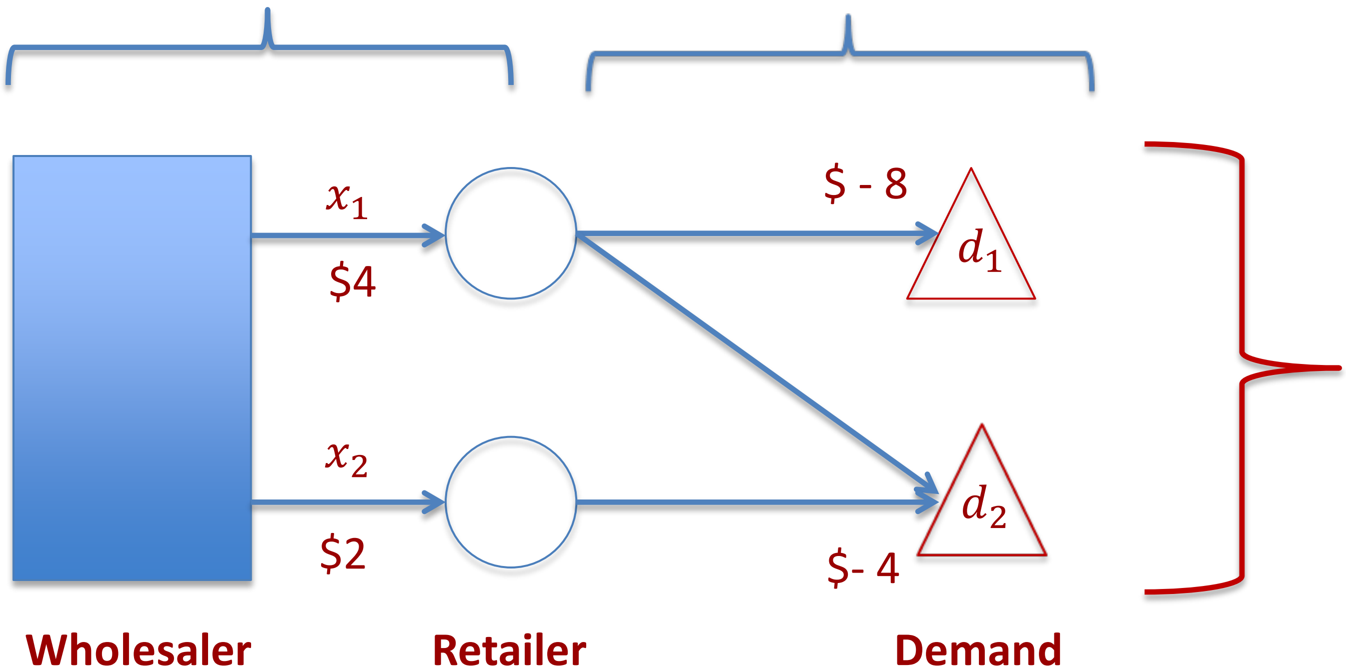


Selling Price 1: $8
Selling Price 2: $4
Backorder Cost: $10
Holding Cost: $0.20

Demands are normally distributed with mean = 100 and std. dev = 12.5

SP for Operations

First stage   Second Stage



Selling Price 1: $8
Selling Price 2: $4
Backorder Cost: $10
Holding Cost: $0.20

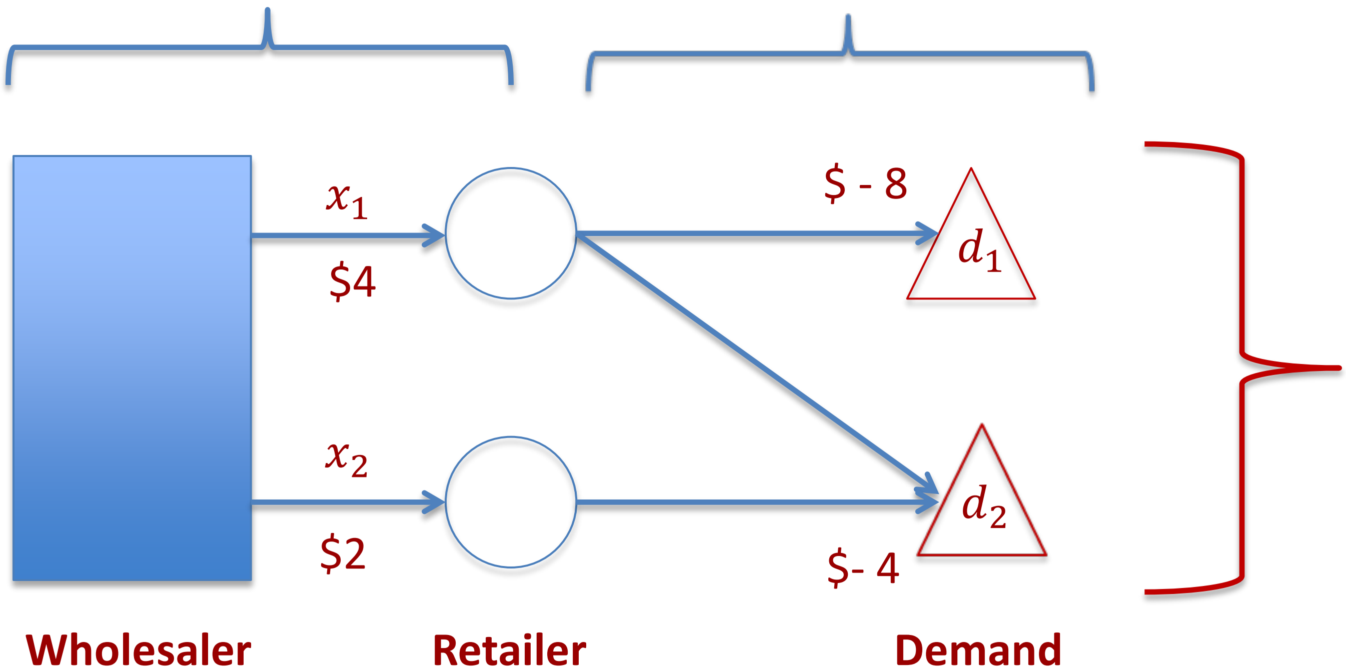
Demands are normally distributed with mean = 100 and std. dev = 12.5

N = ??

UQ for Operations

First stage   Second Stage

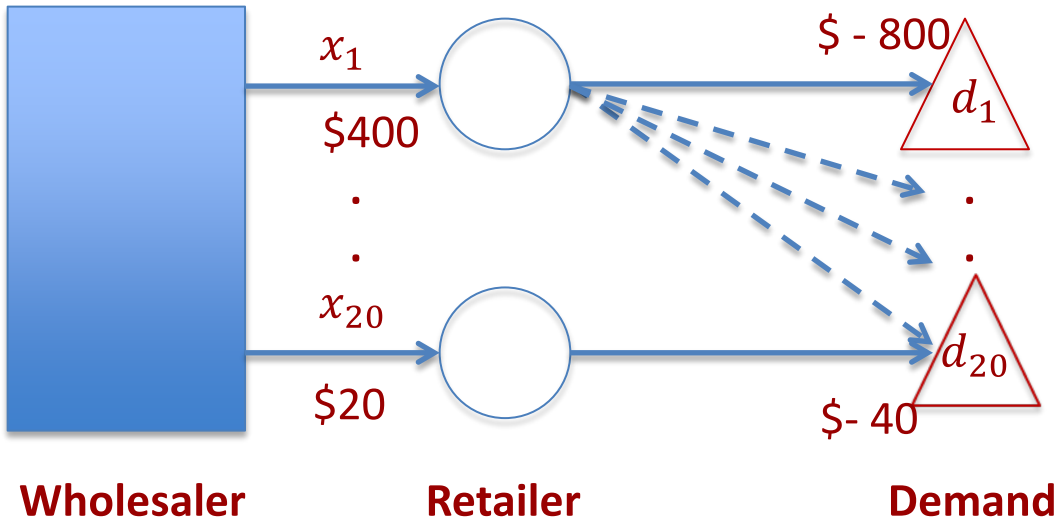
Selling Price 1: $8
Selling Price 2: $4
Backorder Cost: $10
Holding Cost: $0.20



Demands are normally distributed with mean = 100 and std. dev = 12.5

UQ Demo

- 20 products, Normally distributed demands



Stochastic Decomposition: Simultaneously Optimize + Monte Carlo

Note: We do not commit to a sample size before “seeing” the instance. We try to recognizes optimality “on the fly”, thus avoiding unnecessarily large instances.

UQ Engines: SAA and SD

- Sample Average Approximation (Linderoth, Shapiro, Wright; Annals of OR, 2006):
  - **Choose** a sample size;
  - **Optimize** the sampled problem;
  - **Repeat** M times (say M ~ 7 – 10)
  - Sampling Strategy: Latin Hypercube Sampling.
  - Computing Platform: Computing Grid (100s of Desktop PCs)

- Stochastic Decomposition (Sen, Encyclopedia of OR/MS (Springer, 2012)):
    - **Sample** a small number of scenarios (say 1 or more);
    - **Update** a value function approximation;
    - **Optimize** the value function approximation (plus proximal term);
    - **Repeat** until stopping rule is satisfied.
  - **Repeat** M times (say M = 30).
  - Sampling Strategy: Uses Common Random Numbers, and find sample size for each replication
  - Computing Platform: Laptop (Mac Book Air)

UQ Comparisons of SAA and SD using SSN

Sample Average Approximation (Linderoth et al 2006)

Sample Size	Lower Bound	Upper Bound	Pessimistic Gap
SAA-100	8.90(+/- 0.36)	10.542 (+/-0.021)	2.023
SAA-500	9.87 (+/-0.22)	10.069(+/- 0.026)	0.445
SAA-1000	9.83(+/- 0.29)	9.996 (+/- 0.025)	0.445
SAA-5000	9.84 (+/- 0.10)	9.913 (+/- 0.022)	0.195

Stochastic Decomposition (Sen 2012, see also Higle and Sen 1994, 1999)

SD Avg. Sample (St.Deviation)	Lower Bound	Upper Bound	Pessimistic Gap
2212.5 (370.3)	9.76 (+/- 0.16)	9.91 (+/- 0.05)	0.36

Economic Dispatch

Master Problem

min Generation Cost + Expected recourse value

s.t. Generation ramping limits

Generation capacity limits

Recourse Value Function

$h(\{G\},\omega) = \min$ Fast Operating reserves/ramping/buying-selling costs

s.t. Network flow balance equations

Line power flow

Line capacity limits

Wind Availability

Storage limits

Bounds on operating reserves/ramping

Economic Dispatch

Master Problem

$$\min \quad \sum_{i\in\mathcal{G}} c_i G_{hi} + \mathbb{E}\{h(\{G\},\tilde{\omega})\}$$

$$\text{s.t.} \quad \Delta G_i^{min} \le G_{hi} - G_{(h-1)i} \le \Delta G_i^{max} \quad \forall i \in \mathcal{G}$$

$$G_i^{min} \le G_{hi} \le G_i^{max} \quad \forall i \in \mathcal{G}$$

Recourse Value Function

$$h(\{G\},\omega) = \min \quad \sum_{t\in\mathcal{T}} \left(\eta_t^b \sum_{n\in\mathcal{N}} b_{htn} - \eta_t^s \sum_{n\in\mathcal{N}} s_{htn} \right)$$

$$\text{s.t.} \quad \sum_{(j,i)\in\mathcal{A}} p_{htji} - \sum_{(i,j)\in\mathcal{A}} p_{htij} + b_{hti} - s_{hti} + \sum_{j\in\mathcal{W}_i} w_{hti}$$

$$+ \sum_{j\in\mathcal{R}_i} r_{htj} + \sum_{j\in\mathcal{G}_i} G_{hj} = \sum_{j\in\mathcal{D}_i} D_{hj} \quad \forall i \in \mathcal{N}$$

$$p_{htij} = V_i V_j (\theta_i - \theta_j)/X_{ij} \quad \forall (i,j) \in \mathcal{A}$$

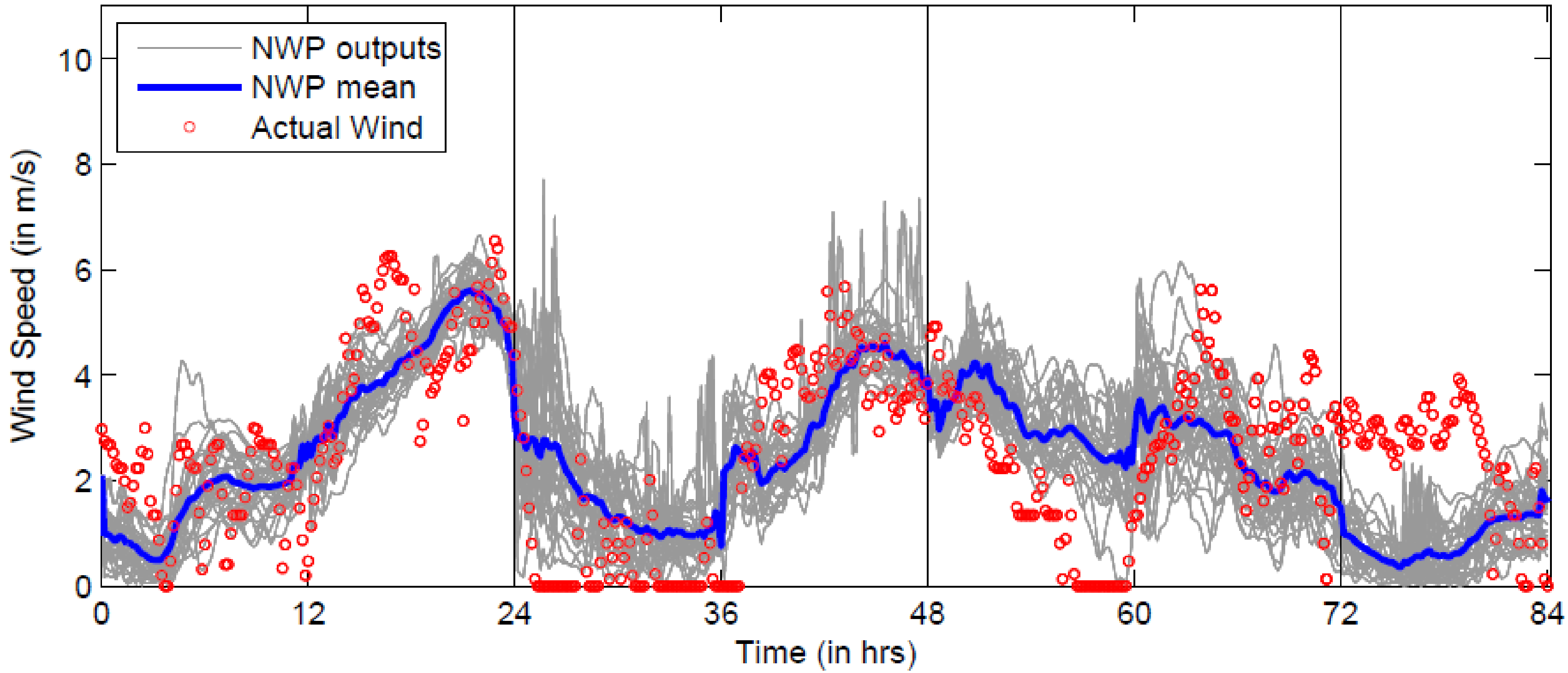
$$p_{ij}^{min} \le p_{htij} \le p_{ij}^{max} \quad \forall (i,j) \in \mathcal{A}$$

$$0 \le w_{hti} \le W_t \quad \forall i \in \mathcal{W}$$

$$r_{hti}^{min} \le r_{hti} \le r_{hti}^{max} \quad \forall i \in \mathcal{R}$$

$$b_{hti}, s_{hti} \ge 0 \quad \forall i \in \mathcal{N}$$

Numerical Wind Prediction

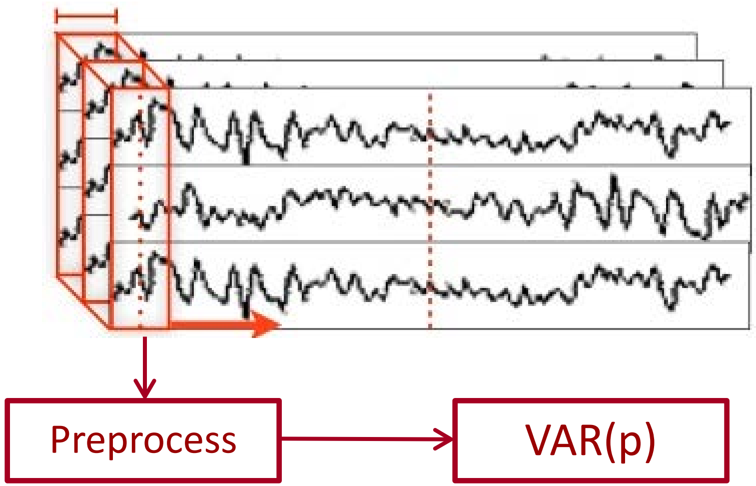


Wind Simulation: Vector Auto-regression

$$VAR(p): \quad y_t = \boxed{\epsilon_t} + A_1 y_{t-1} + \dots A_p y_{t-p} + \boxed{\eta_t}$$

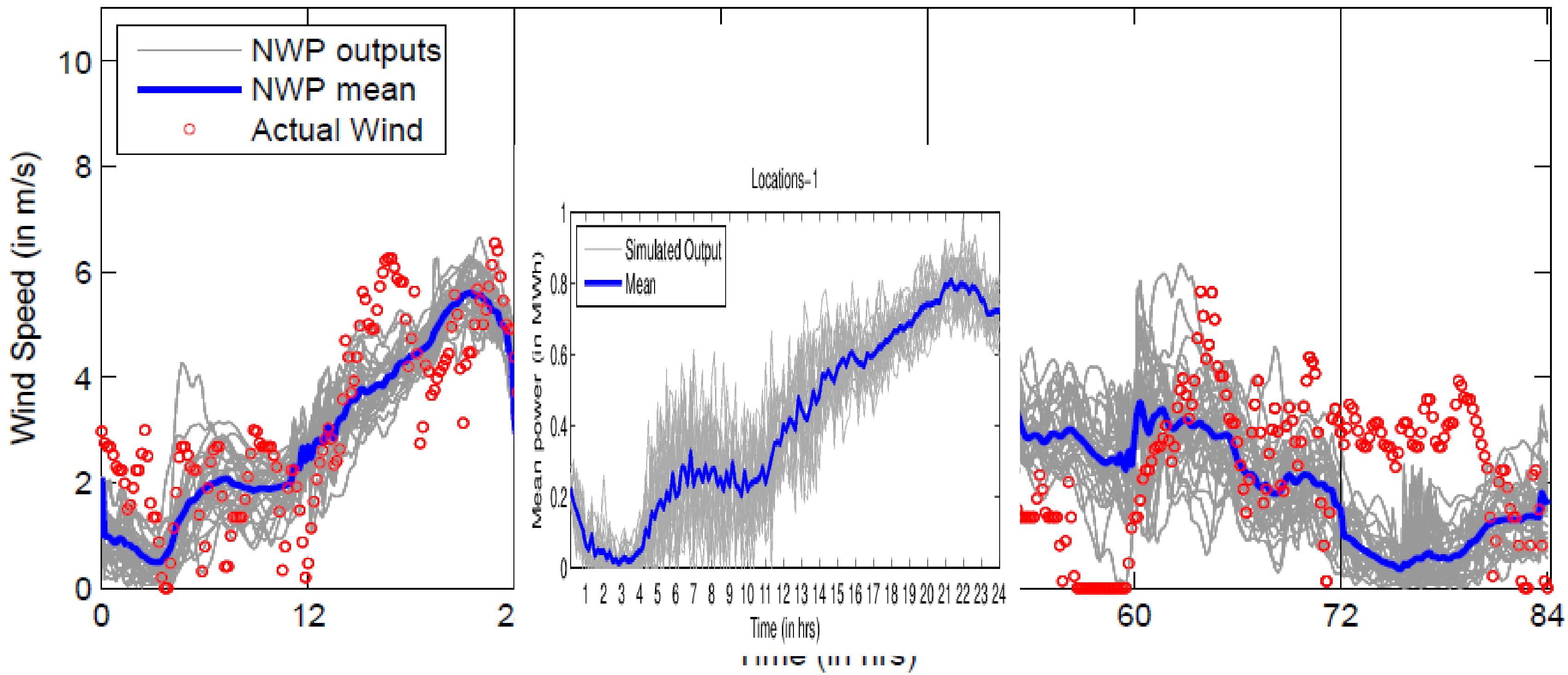
Deterministic regressors

White noise



- Segment Adaptive VAR
- Captures **spatio-temporal** correlations
- Information criterion (Bayes-Schwartz) based model selection
- Validated from residual whiteness, stability and consistency.

Simulated Wind Model



Stochastic Decomposition (Hourly Simulation)

Master Problem

$$\begin{aligned} \min \quad & c^\top \mathbf{G}_h + \mathbb{E}\{\psi(\mathbf{G}_h, \tilde{x}_h)\} \\ s.t. \quad & \mathbf{G}_h \in \Gamma_G \end{aligned}$$

$\mathbf{G}^k$

Subproblem

SMPS

Stoch file

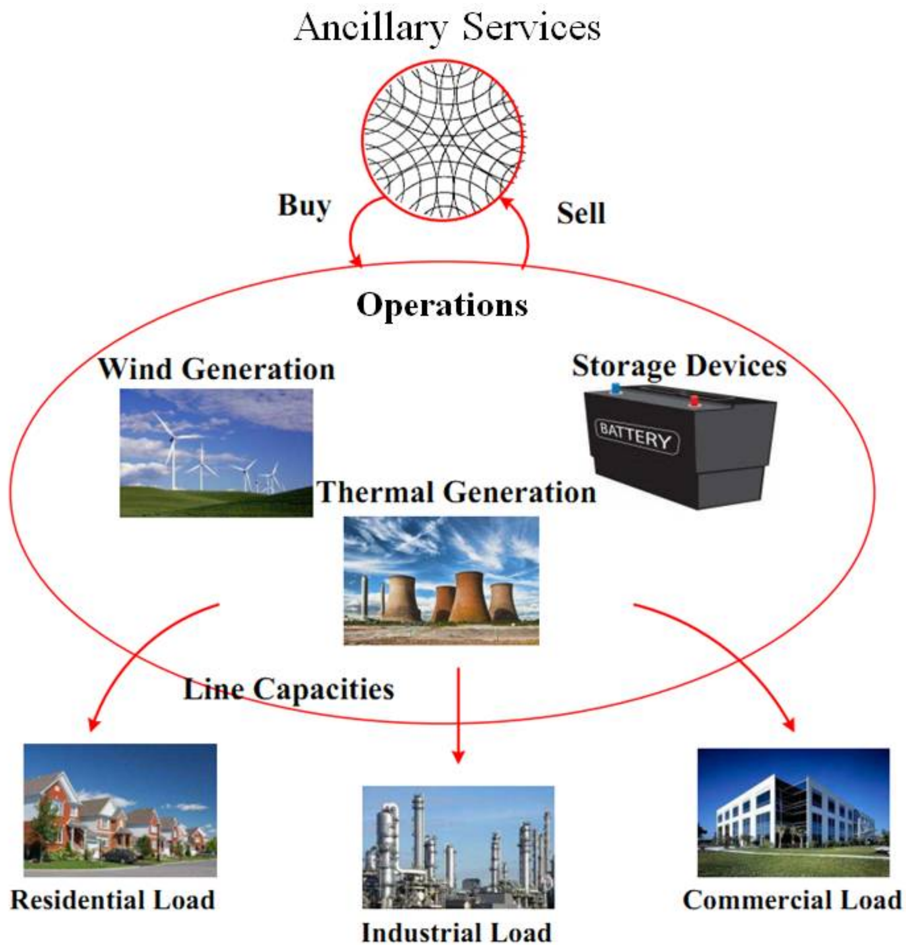
Wind Simulator

Vector Auto-Regression

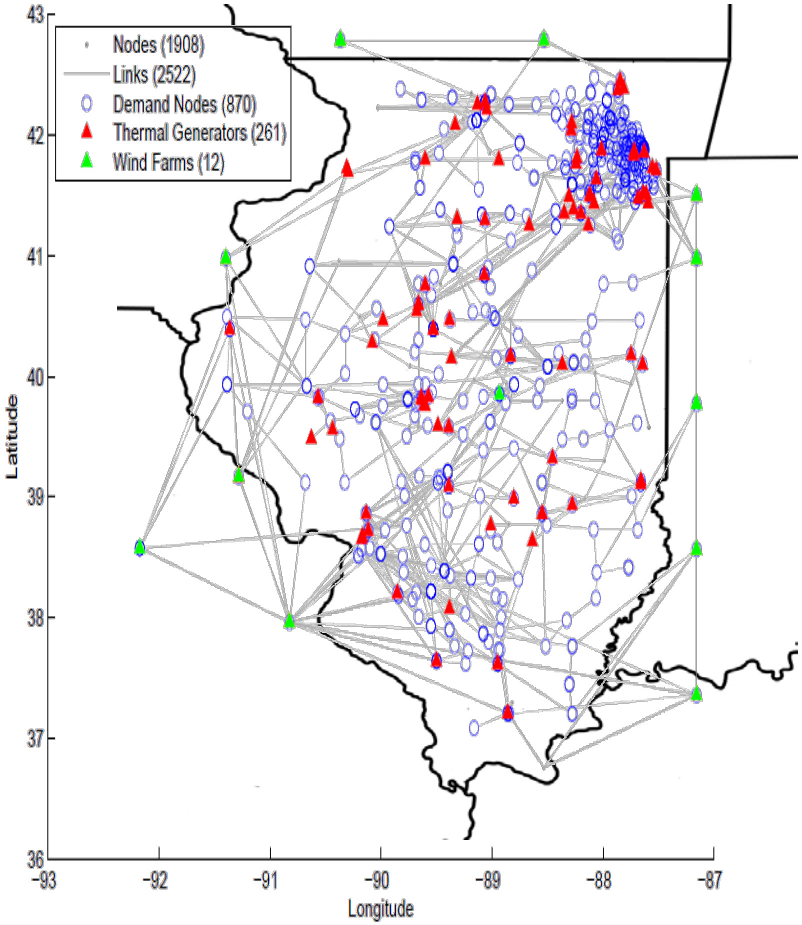
$$\begin{aligned} \psi(\mathbf{G}_h, x_h) = \quad \min \quad & \mathbf{g}^\top \mathbf{y}_h \\ s.t. \quad & \mathbb{W}\mathbf{y}_h = \vec{\rho}(x_h) - \mathbb{T}\mathbf{G}_h \\ & \mathbf{Y}_h \in \Gamma_y \end{aligned}$$

$\Psi_*^k(\mathbf{G})$

The Economic Dispatch Setting



The Data: Illinois Network (12 Wind Farms)



Master:
- Columns - 261
- Rows - 522

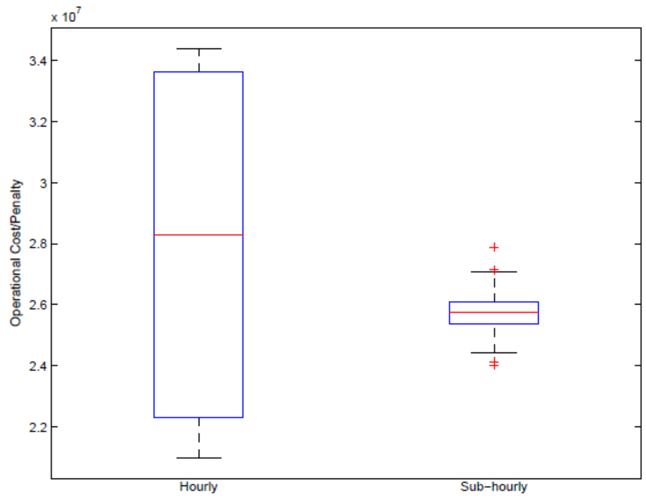
Sub-problem:
- Columns - 33510
- Rows – 26658
- Wind farms - 12

UQ Results: Hourly vs. Sub-hourly

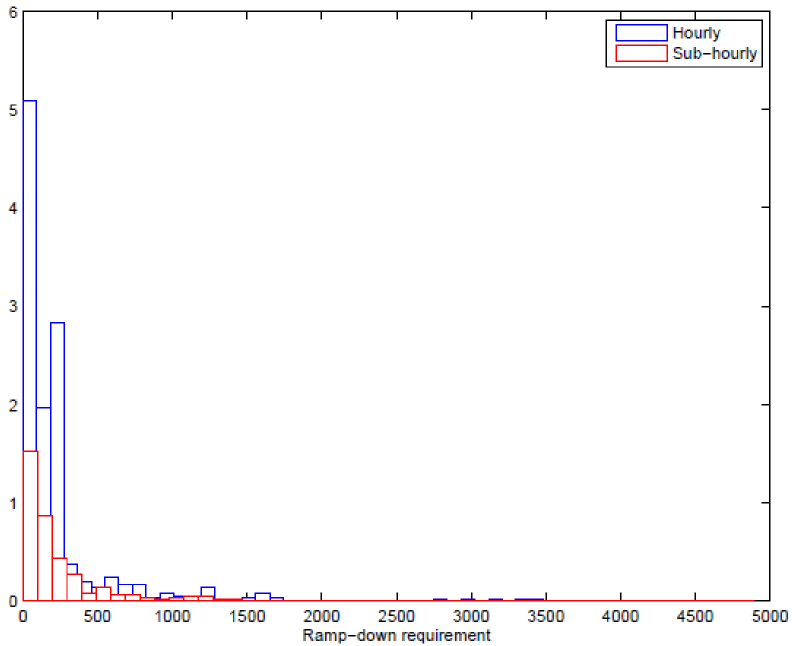
Conventional Generation Planning:

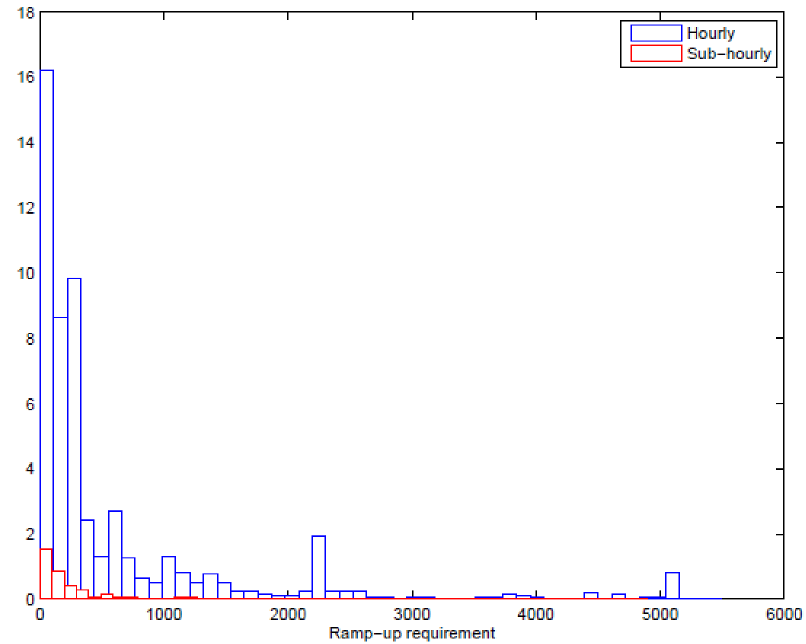
	Hourly Planning	Sub-hourly Planning
Total generation (MWh)	8.8812×10^4	9.2073×10^4
Generation cost ($)	6.9862×10^6	7.2614×10^6

Operating Costs/penalties:



UQ Results: Hourly vs. Sub-hourly





Histogram of operating reserve requirement under the two plans

UQ performance: Hourly & Sub-hourly

Processor: Inter Core i7-2600 @ 3.4GHz x 8; Platform: Ubuntu 12.04(64 bit)

Scenarios SOLVER	Hourly Planning			Sub-hourly Planning		
	SAA-10 CPLEX (Def)	**SAA-25** CPLEX (Def)	SD	**SAA-10** CPLEX (Def)	**SAA-25** CPLEX (Def)	SD
Rows	52260	130650	522 4443	274410	844275	522 26658
Columns	58460	140150	261 5585	337709	686025	261 33510
RV's	-	-	12	-	-	72
Iterations	54494	256137		455720	682372*	
Time (s)	341.13	5016.05		31237.52	78939.23*	

*Run aborted

UQ performance: Hourly & Sub-hourly

Processor: Inter Core i7-2600 @ 3.4GHz x 8; Platform: Ubuntu 12.04(64 bit)

	Hourly Planning			Sub-hourly Planning		
	CPLEX (Def) **10 Scenarios**	CPLEX(Def) **25 Scenarios**	SD	CPLEX(Def) **10 Scenarios**	CPLEX(Def) **25 Scenarios**	SD
Rows	52260	130650	522 4443	274410	844275	522 26658
Columns	58460	140150	261 5585	337709	686025	261 33510
RV's (Sample)	-	-	12 (913)	-	-	72
Iterations	54494	256137	**913**	455720	682372*	
Time (s)	341.13	5016.05	**446.06**	31237.52	78939.23*	

*Run aborted

UQ performance: Hourly & Sub-hourly

Processor: Inter Core i7-2600 @ 3.4GHz x 8; Platform: Ubuntu 12.04(64 bit)

	Hourly Planning			**Sub-hourly Planning**		
	CPLEX (Def) **10 Scenarios**	CPLEX(Def) **25 Scenarios**	SD	CPLEX(Def) **10 Scenarios**	CPLEX(Def) **25 Scenarios**	SD
Rows	52260	130650	522 4443	274410	844275	522 26658
Columns	58460	140150	261 5585	337709	686025	261 33510
RV's (Sample)	-	-	12 (913)	-	-	72 (1513)
Iterations	54494	256137	**913**	455720	682372*	**1513**
Time (s)	341.13	5016.05	**446.06**	31237.52	78939.23*	**17941.55**

*Run aborted

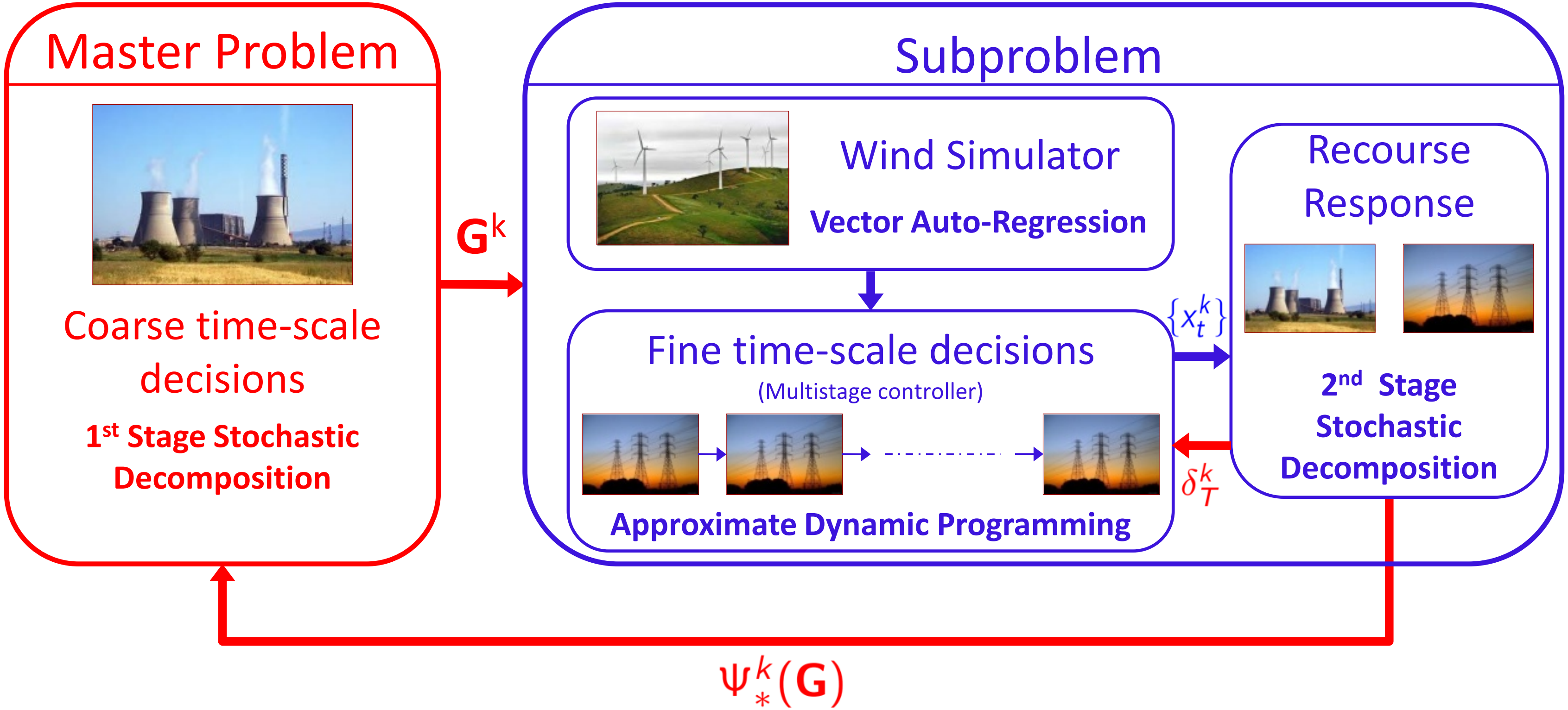
Main Take Away

- Can SP Technology Provide Realistic Decision Support for Hourly Dispatch with Hourly Wind Simulation?
  - Yes, absolutely!
- Can SP Technology Provide Realistic Decision Support for Hourly Dispatch with Sub-hourly Wind Simulation?
  - Yes, with a bit of tuning! (e.g. Upper and Lower Bounds are within 0.1% of each other. Do we need that? NO!)

- Increased Computing Power =>

  Time to Combine Optimization + Statistics
  - (Not to Abandon it!)

Combining SP and Optimal Control



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Stochastic UC as Two-stage SMIP

- **Binary First Stage (Start-up, ramping …)**
- **Continuous Second-Stage (LPs)**

- **Algorithm** (Uses General Stochastic MIP Method)
  – Use UQ with Stochastic Decomposition for Two-stage **SLP**
  – Correct Fractional Solutions Using Strong Relaxations for **First-stage SIP**