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# Stochastic Unit Commitment for the Day-Ahead Market and Resource Adequacy Assessment

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*Iowa State University*

# Scalable, Parallel Stochastic Unit Commitment for Improved Day-Ahead and Reliability Operations

Presented in “Modeling, Simulation and Optimization for the 21$^{st}$ Century Electric Power Grid”

# Project Team

- Sandia National Laboratories
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  - Jean-Paul Watson, PhD
  - Cesar Silva Monroy, PhD
- Iowa State University
  - Sarah Ryan, PhD
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- Alstom Grid
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  - Roger Wets, PhD
  - David Woodruff, PhD
- ISO New England
  - Eugene Litvinov, PhD

# External Advisors

- Eugene Litvinov, ISO-NE
  - Chairs Advisory Team
- Richard O'Neill, FERC
- Ralph Masiello, KEMA
- David Morton, UT Austin

# Project Goals

- Execute <u>*stochastic*</u> unit commitment (UC) ***at scale***, ***on real-world data sets***
  - Stochastic UC state-of-the-art is very limited (tens to low hundreds of units)
  - Our solution must ultimately be useable by an ISO
- Produce solutions ***in tractable run-times***, ***with error bounds***
  - Parallel scenario-based decomposition
    - For both upper and lower bounding (Progressive Hedging and Dual Decomp.)
  - Quantification of uncertainty
    - Rigorous confidence intervals on solution cost
- Employ high-accuracy stochastic process models
  - Leveraged to achieve computational tractability while maintaining solution quality and robustness
- Demonstrate ***cost savings on an ISO-scale system*** at ***high renewables penetration levels***

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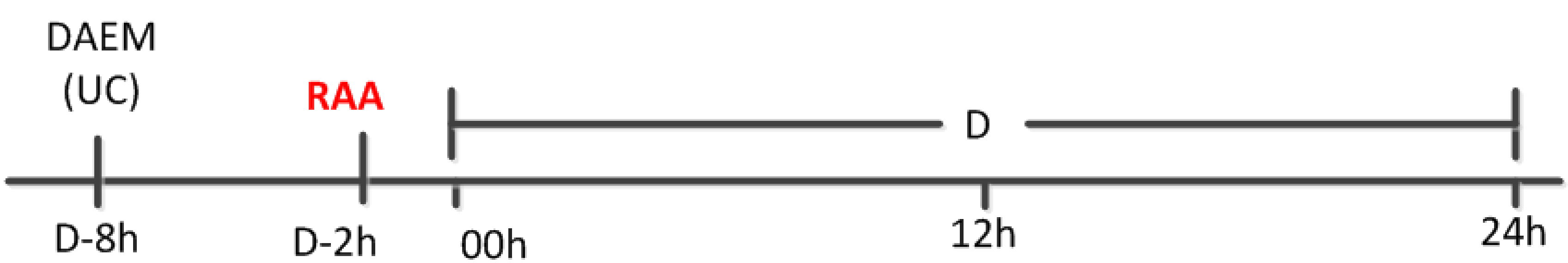
# Day-Ahead Unit Commitment (SCUC D-8h)

- Day-Ahead Energy Market (DAEM or DAM)
- Clears **demand bids** and **supply offers** at 1600h on the day prior to the operating day
- Produces:
  - Hourly schedules for the next operating day for market participants (i.e., generation and demand)
  - Hourly interchange schedules
  - Hourly day-ahead Locational Marginal Prices (LMPs)
- **No reserve requirements**

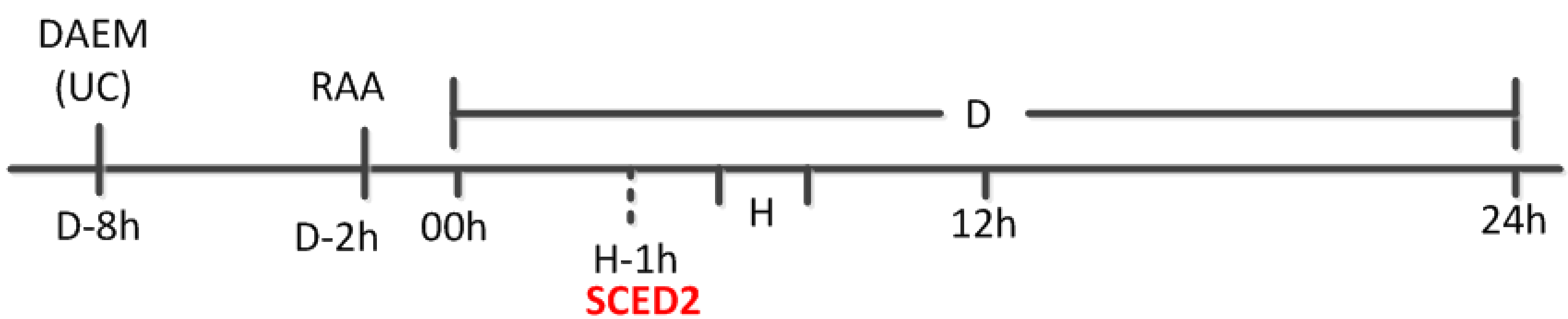
# Reliability Unit Commitment - RUC (SCUC D-2h)

- Reliability Assessment (Reserve Adequacy Analysis - RAA)
- Minimize additional start-up and no load costs to provide sufficient capacity to satisfy the forecasted load plus the **operating and replacement reserve requirements**
- Clears ISO **forecasted load** at 2200h
- DAM commitments are respected
- Produces:
  - Additional commitments
  - Updated generator dispatch points



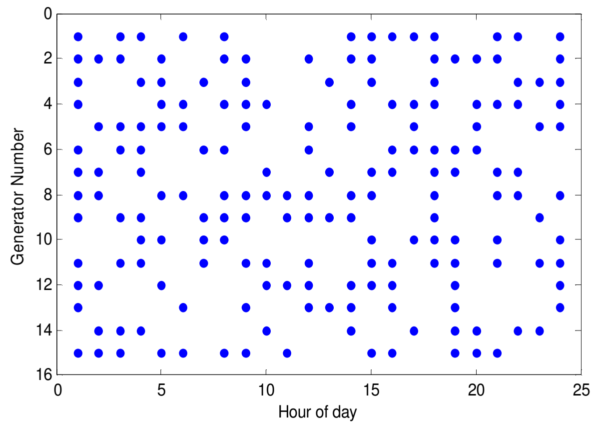
# SCED2 (H-1h)

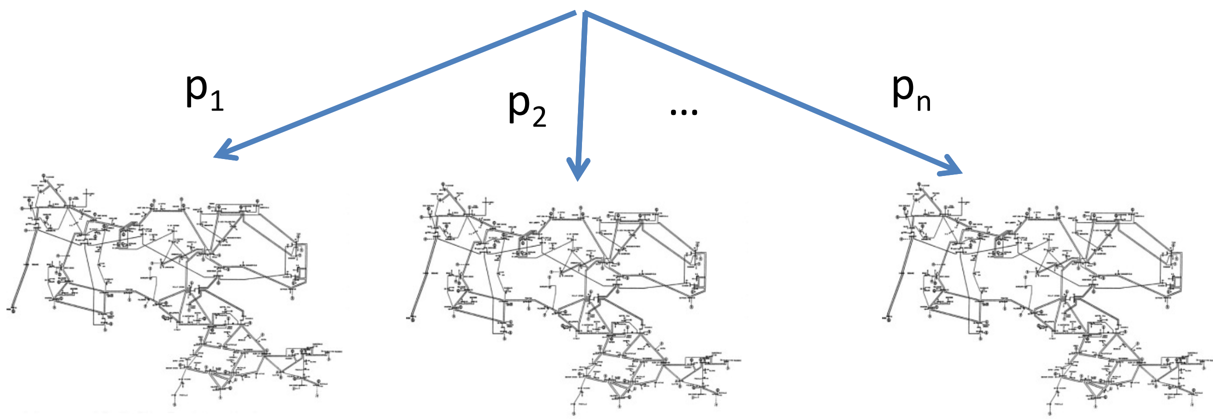
- SCED with ability to bring online fast start resources
- Intended to meet intra-hour reserve requirements
- Updated load and variable generation forecasts
- It produces:
  - Generator setpoints
  - Commitment of fast start units



# General UC Model Structure

Objective: Minimize expected cost




Scenario 1 Scenario 2 … Scenario n

First stage variables:

- Unit On / Off

Nature resolves uncertainty

- Renewables output
- Forced outages

Second stage variables (*per time period*):

- Generation levels
- Power flows
- Voltage angles
- …

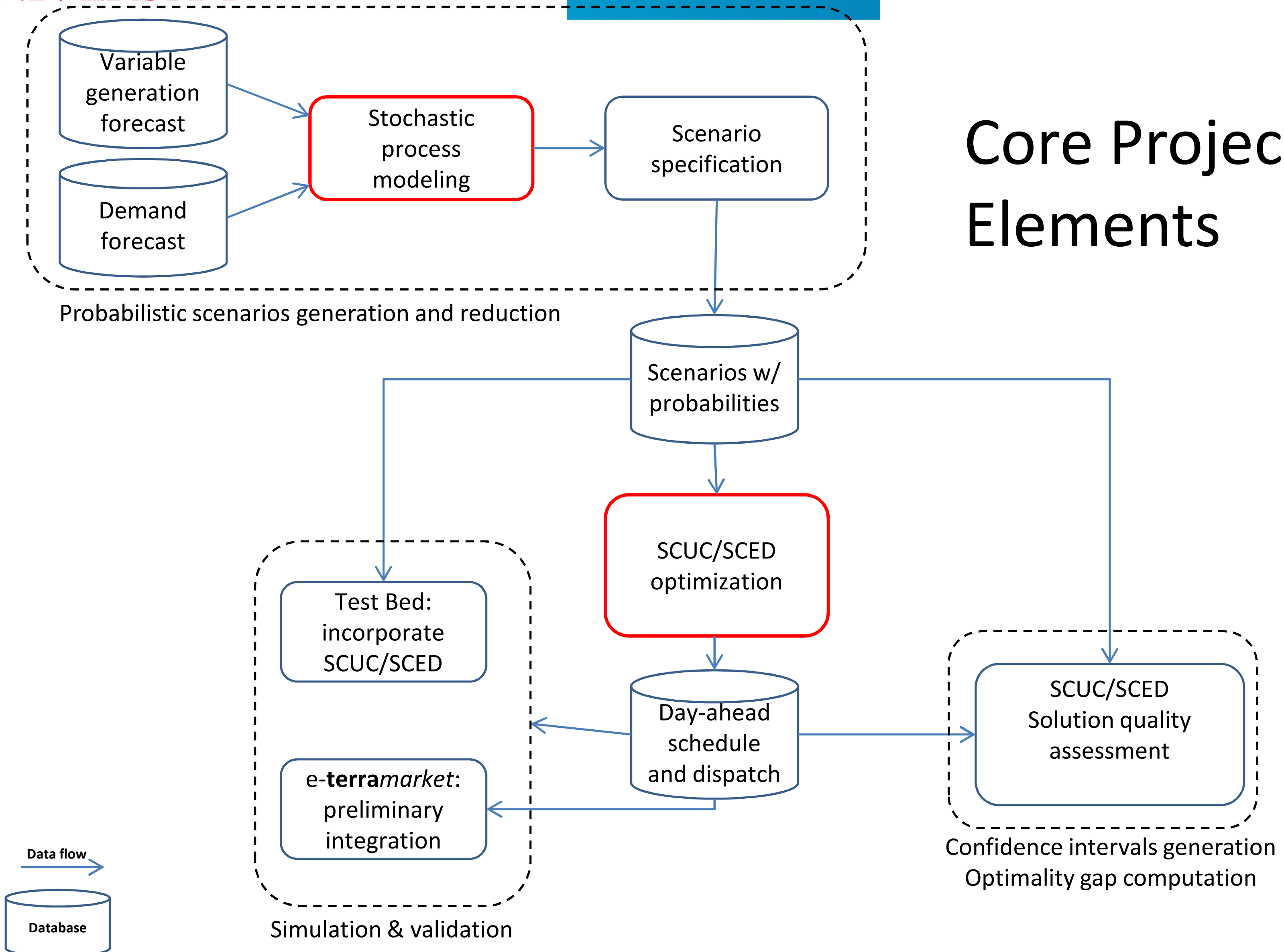
# Uncertainty in DAM, RUC, and SCED2 Stochastic Programming Models

- Reliability Unit Commitment
  - Renewables generator output, load, forced (unplanned) outages
  - Fewer binaries than DAM, long time horizon, many scenarios

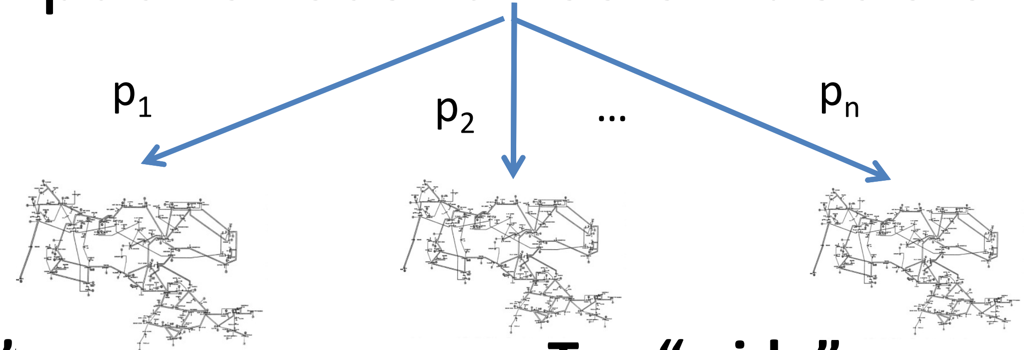
- Look-Ahead Unit Commitment
  - Similar to Reliability Unit Commitment
  - Fewer binaries than RUC, short time horizon, few scenarios

- Day-Ahead Unit Commitment
  - In contrast to RUC and SCED2, an ISO can't really make direct use of a stochastic UC in the DAM without changing DAM procedures
  - With our partners, we are exploring alternative models and experimenting with procedures that incorporate stochastic models
  - We are eager to discuss ideas offline

# Core Project Elements



# Impact of scenarios on decisions



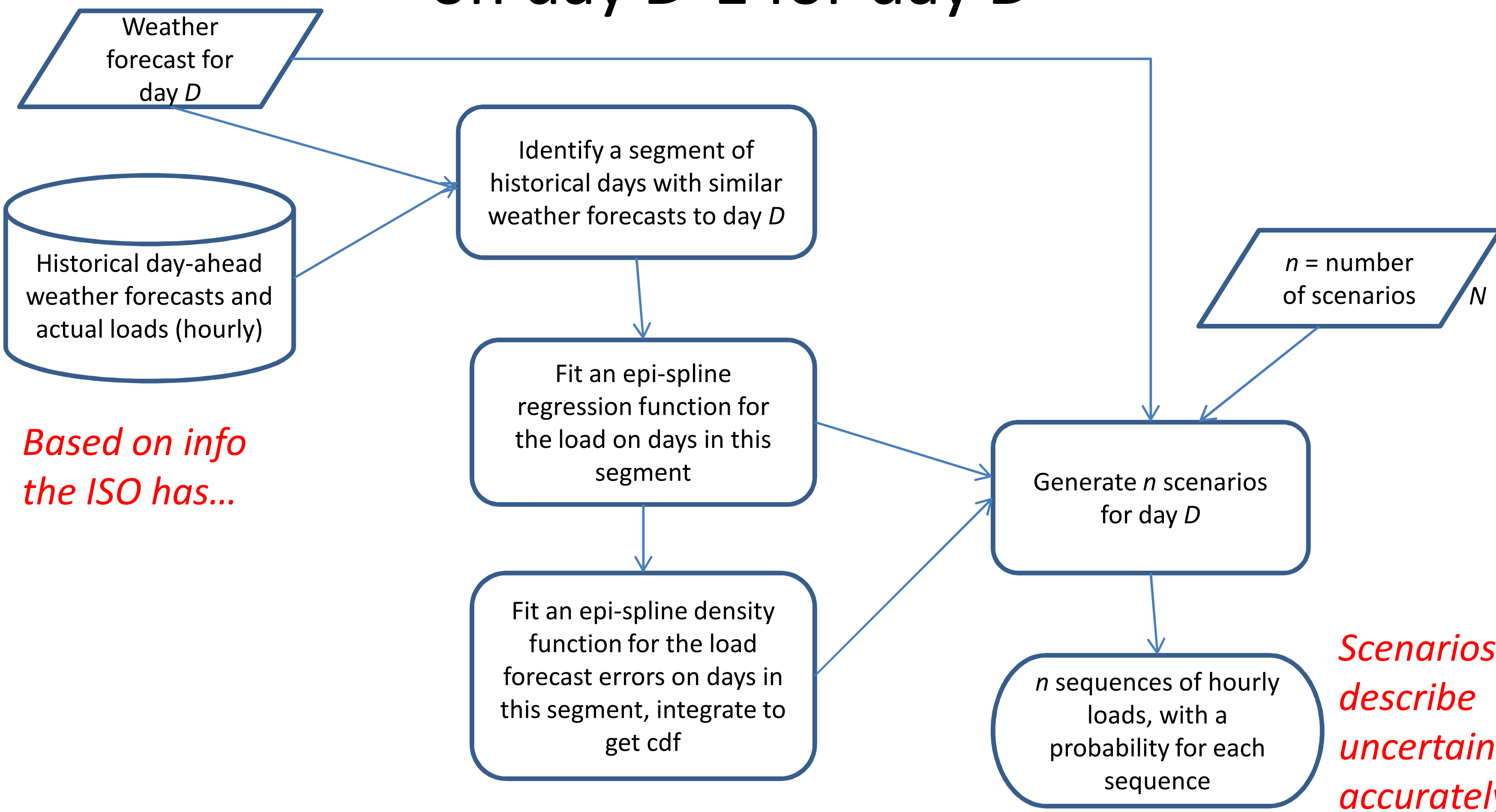

**Too "narrow"**

- Optimization fails to account for actual risks
- Too few low-cost units committed
  - Cost: Start up additional high-cost units
  - Reliability: Shed load

**Too "wide"**

- Optimization result is too risk-averse
- Too many low-cost units committed
  - Cost: Excessive no-load cost of committed units
  - Environmental: spill variable generation

# Overview of process to generate load scenarios on day *D*-1 for day *D*




*Based on info the ISO has…*

*Scenarios describe uncertainty accurately*

# Identify data segment

- Separate by seasons
  - Diurnal light patterns, heating vs. cooling, impact of wind and humidity (RealFeel temperature)
- Within a season
  - Transform every day to “Wednesday” based on average load patterns
  - Cluster based on similarity of weather forecasts
  - For hour *h* on day *j*, ISO-NE data has
    - Forecast temperature from day *j*-1, $t_h^j$
    - Forecast dewpoint temperature from day *j*-1, $d_h^j$
    - Actual load, $l_h^j$

# Fit epi-spline regression function

- Model: $l(r) = z^t(r)t(r) + z^d(r)d(r)$
  where $l(r)$, $t(r)$, $d(r)$ are load and weather variables as functions of continuous time, $r$, and the regression functions $z^t(r), z^d(r)$ are twice-differentiable.
- Approximate $z^t(r), z^d(r)$ with epi-splines $s^t(r), s^d(r)$ that have piecewise constant second derivatives
- Measure errors as $e_h^j = l_h^j - s^t(h)t_h^j + s^d(h)d_h^j$
- Optimization problem

$$\min_{s_0, v_0, \{a_i, i=1,\ldots,N\}} \left\| e = \left(e_h^j, h = 1,\ldots,24; j \in J\right) \right\|_p$$

# Advantages of the epi-spline regression

- Rich family of possible curves, not just polynomials
- Nonparametric estimation of hourly load patterns
- Does not involve lagged loads
- No assumptions about error distributions, e.g., white noise
- Can add constraints based on “soft information” – compensate for small segmented data sets
  - Values: do not underestimate peak loads
  - Slopes: understand daily patterns of increase/decrease
  - Curvature: (so far, bounds have not had much impact)

# Obtain error distribution for each hour

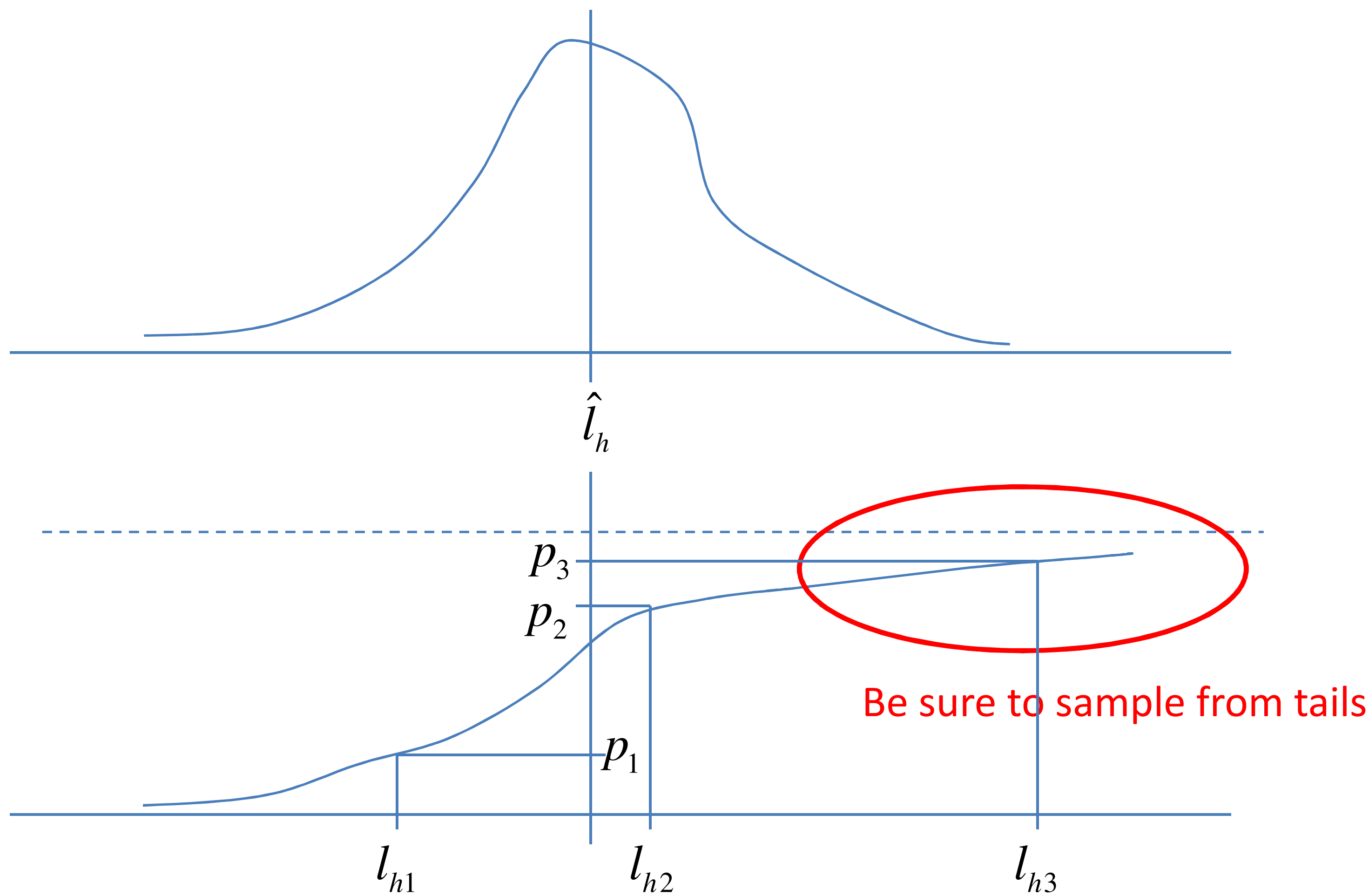
- For hour *h*, compute mean and standard deviation of errors in the segment
- Let $\alpha = \min\left\{\left(e^j, j \in J\right), \bar{e} - 3\sigma_e\right\}, \beta = \max\left\{\left(e^j, j \in J\right), \bar{e} + 3\sigma_e\right\}$
- Approximate error density as

$$f\left(x\right) = e^{-w(x)}, x \in \left[\alpha, \beta\right]$$

where *w*(*x*) is an epi-spline having piecewise constant second derivatives $a_k \in \left[0, \kappa\right]$

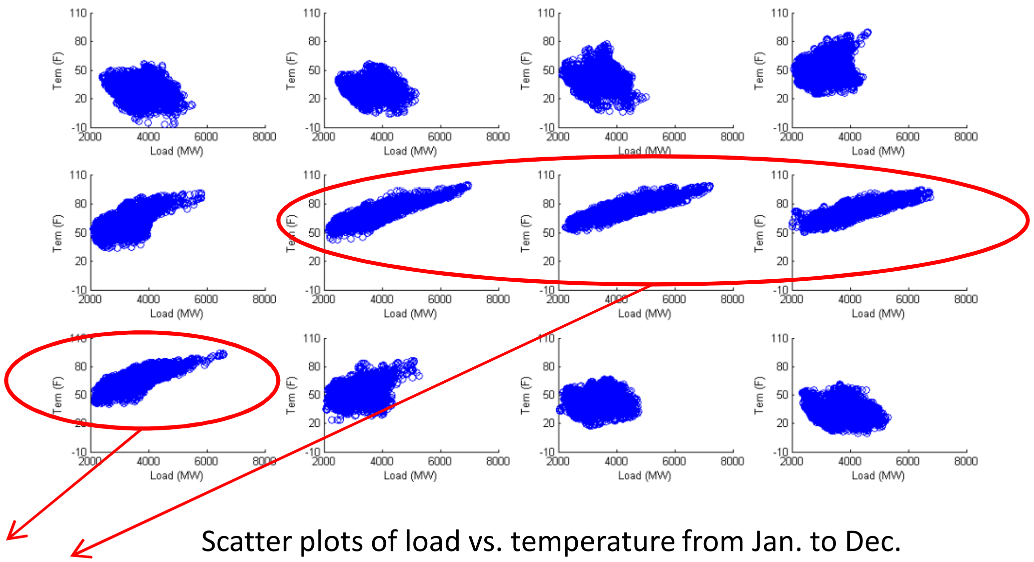
- For numerical reasons, translate domain to [0, $\beta$-$\alpha$] and then rescale to [0,1]
- Maximize likelihood of the observed errors
  - Convex objective function
  - Linear constraints
- Integrate density to obtain cumulative distribution function

# Generate scenarios for hour *h*



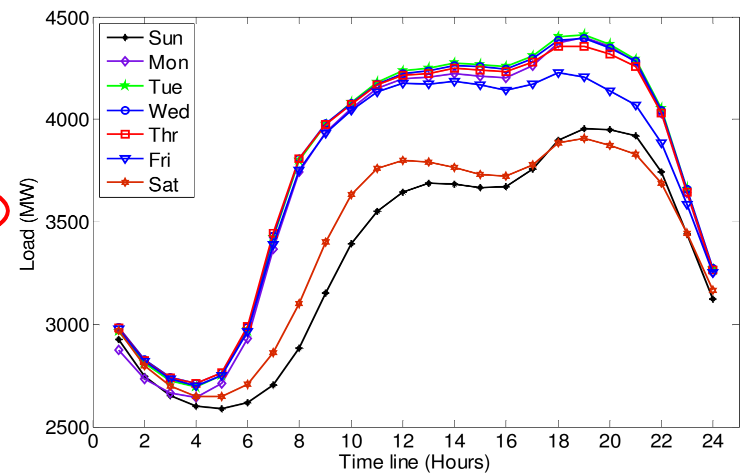
# Progress on segmentation – CT load zone

- Identification of seasons and day-types




Scatter plots of load vs. temperature from Jan. to Dec.

“Summer ”, similar shapes



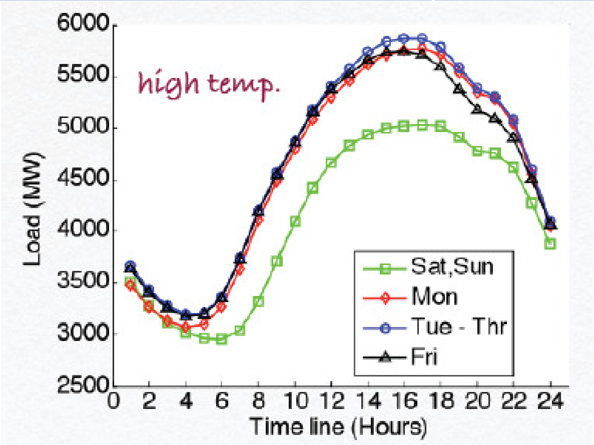

Average load curve of each day in summer

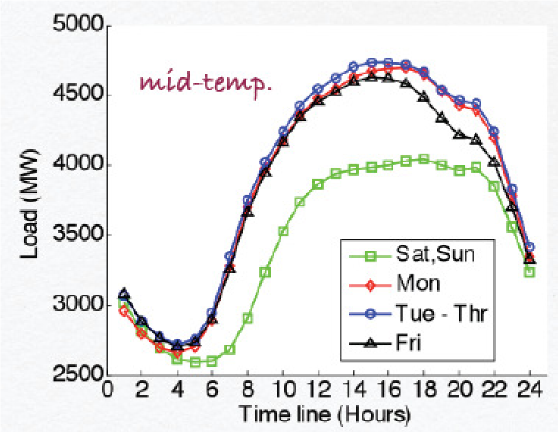
- Similar shapes from Tue. to Thr.
- Differences appear on Mon., Fri., Sat. and Sun.

# Clustering based on weather forecast

1. Hourly temperature sequence as an observation vector;
2. Create clusters within a season by k-means

| Summer clusters | Hot days | Moderate days | Cool days |
|---|---|---|---|
| Mean temperature (F) | 78.29 | 71.04 | 62.52 |
| Mean Dew point temp. (F) | 65.16 | 59.86 | 51.75 |
| Days | 81 | 125 | 78 |



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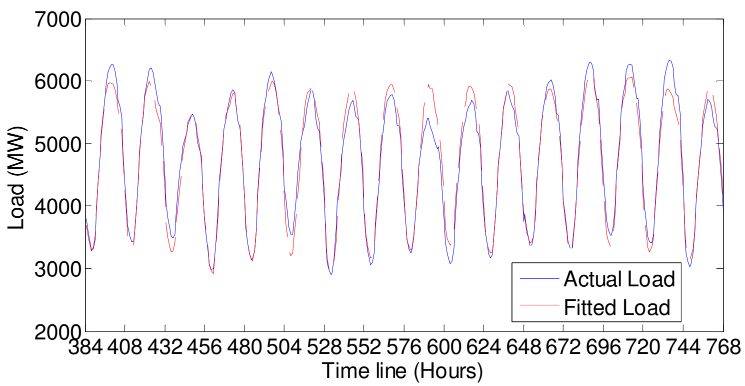
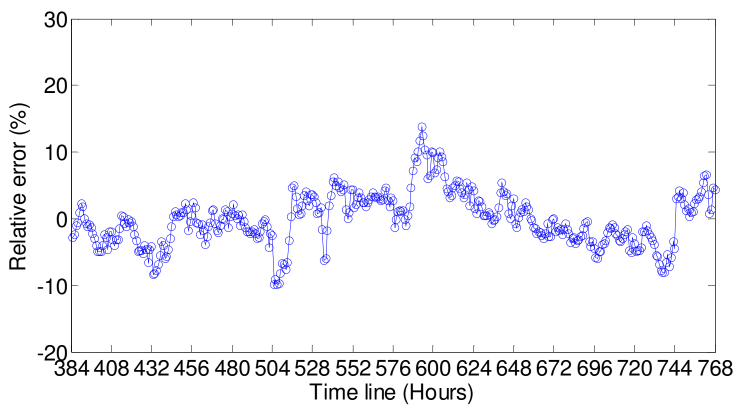
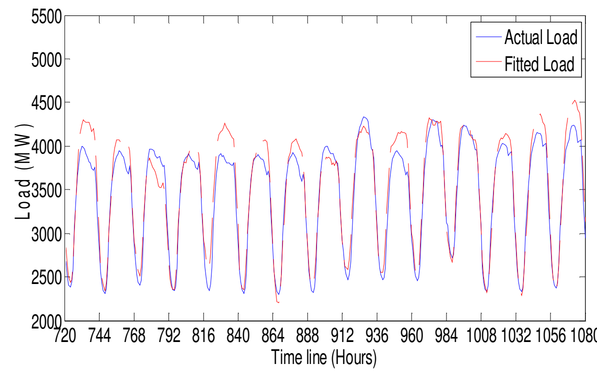
# Preliminary load fitting results

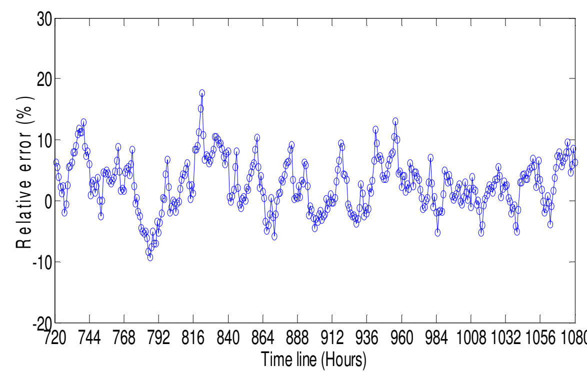
Hot summer days: MAPE = 5.05 %



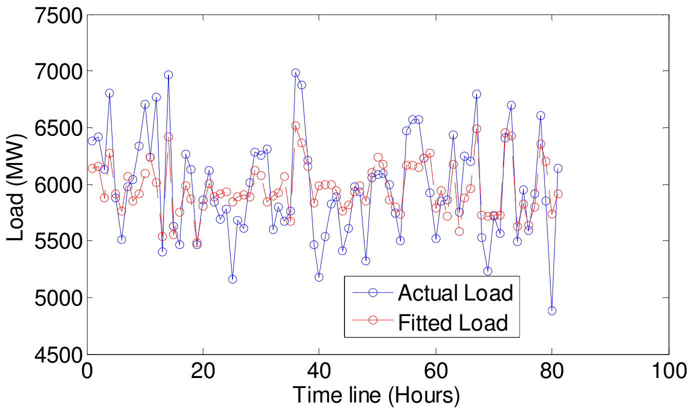

Cool summer days: MAPE = 4.52%

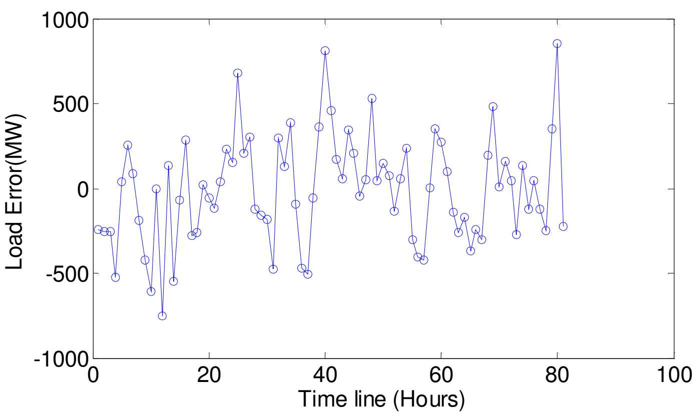


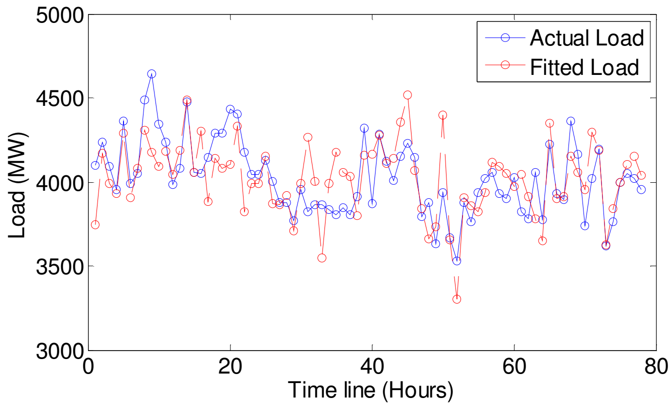
# Errors in peak load hour

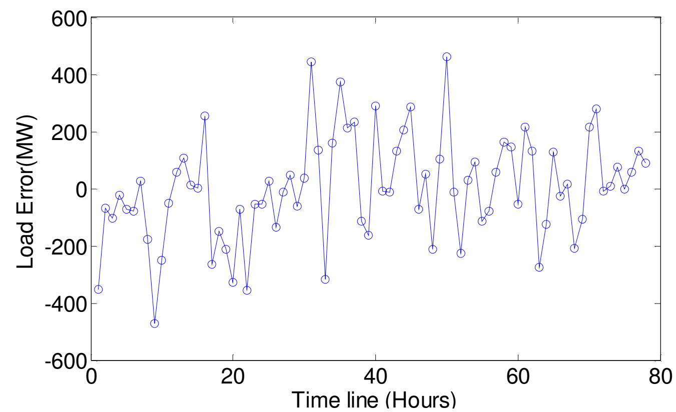
## Hot summer days



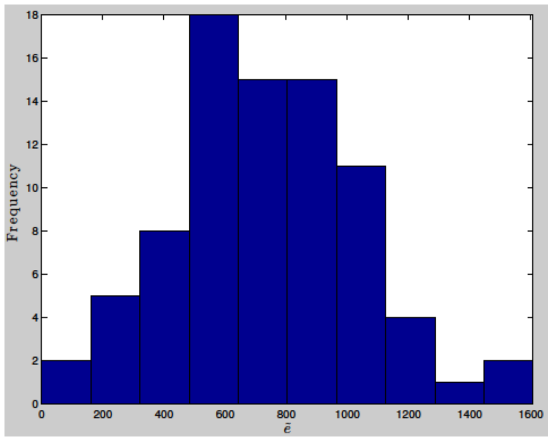

## Cool summer days



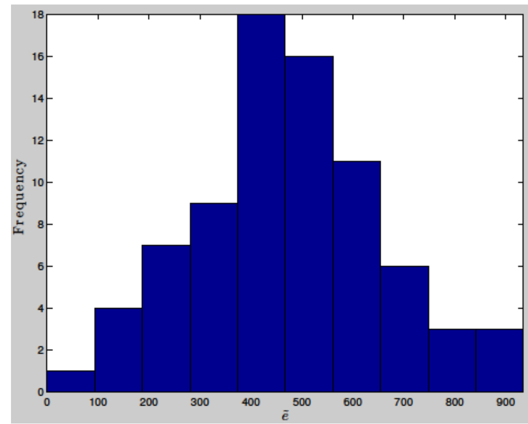



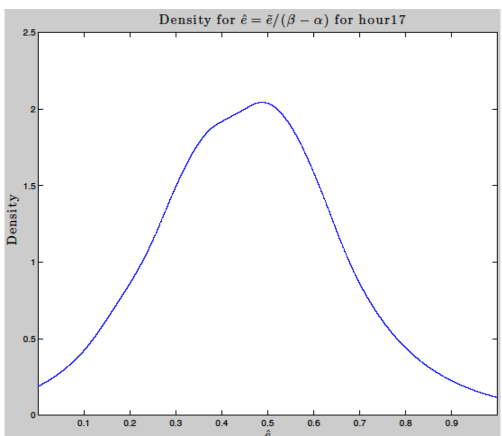
# Error densities for peak load hour

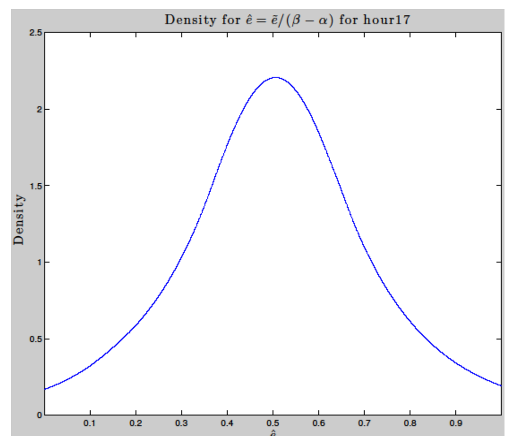
Hot summer days




Cool summer days



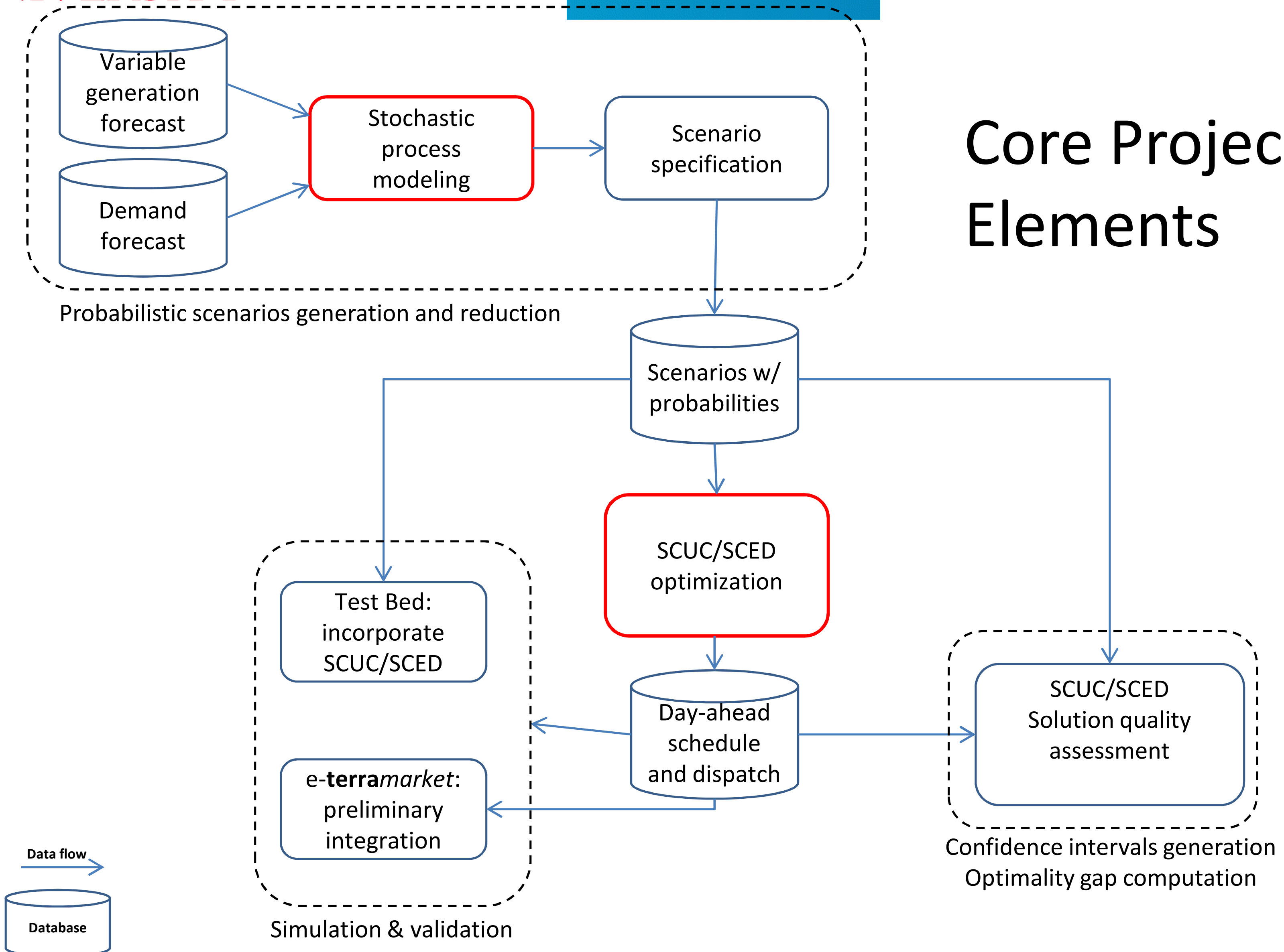



# Wind power scenarios: working with 3TIER, Inc.

- From Eastern Wind Integration and Transmission Study (EWITS) high penetration futures for New England
  - For day *D*, identify segment of past days with similar weather conditions
  - Provide weather forecast, “actual” wind power for each day in segment along with a similarity weight
- We can apply same scenario generation approach as for load
- Scenarios for load and wind power will be drawn from *joint* distributions based on weather conditions.

# Core Project Elements



# Scenario-based decomposition via Progressive Hedging (PH)

1. $k := 0$
2. For all $s \in \mathcal{S}$, $x_s^{(k)} := \text{argmin}_x (c \cdot x + f_s \cdot y_s) : (x, y_s) \in \mathcal{Q}_s$
3. $\bar{x}^k := (\sum_{s \in \mathcal{S}} p_s \, d_s x_s^{(k)}) / \sum_{s \in \mathcal{S}} p_s \, d_s$
4. For all $s \in \mathcal{S}$, $w_s^{(k)} := \rho(x_s^{(k)} - \bar{x}^{(k)})$
5. $k := k + 1$
6. For all $s \in \mathcal{S}$, $x_s^{(k)} := \text{argmin}_x (c \cdot x + w_s^{(k-1)} x + \rho/2 \left\| x - \bar{x}^{(k-1)} \right\|^2 + f_s \cdot y_s)$ $: (x, y_s) \in \mathcal{Q}_s$
7. $\bar{x}^{(k)} := (\sum_{s \in \mathcal{S}} p_s \, d_s x_s^{(k)}) / \sum_{s \in \mathcal{S}} p_s \, d_s$
8. For all $s \in \mathcal{S}$, $w_s^{(k)} := w_s^{(k-1)} + \rho \left( x_s^{(k)} - \bar{x}^{(k)} \right)$
9. $g^{(k)} := \frac{(1-\alpha)|\mathcal{S}|}{\sum_{s \in \mathcal{S}} p_s \, d_s} \sum_{s \in \mathcal{S}} \left\| x^{(k)} - \bar{x}^{(k)} \right\|$
10. If $g^{(k)} < \epsilon$, then go to step 5. Otherwise, terminate.

*Rockafellar and Wets (1991)*

# Progressive Hedging: Some algorithmic issues and their resolution

- We are dealing with mixed-integer programs
  - So we have to deal with the possibility of cycling and other manifestations of non-convergence
  - See: *Progressive Hedging Innovations for a Class of Stochastic Mixed-Integer Resource Allocation Problems*, J.P. Watson and D.L. Woodruff, Computational Management Science, Vol. 8, No. 4, 2011

- What about good values for that pesky ρ parameter?
  - Poor or ad-hoc values of ρ can lead to atrocious performance
  - The good news in unit commitment
    - We have a lot of information concerning the cost of using a generator
    - Cost-proportional ρ is a known, effective strategy in Progressive Hedging
  - Also see Computational Management Science paper indicated above

# Progressive Hedging: Parallelization and bundling

- Progressive Hedging is, at least conceptually, easily parallelized
  - Scenario sub-problem solves are clearly independent
  - Advantage over Benders, in that “bloat” is distributed
    - Critical in low-memory-per-node cluster environments
  - Parallel efficiency drops rapidly as the number of processors increases
    - But: *Relaxing barrier synchronization does not impact PH convergence*

- Why just one scenario per processor?
  - Bundling: Creating miniature “extensive forms” from multiple scenarios
    - Diverse or homogeneous scenario bundles?
  - Empirically results in a large reduction in total number of PH iterations
    - Growth in sub-problem cost *must* be mitigated by drop in iteration count
    - In practice, mitigation is enabled by cross-iteration warm starts

# Illustrative results: WECC-240

- Test instance
  - Modified WECC-240 instance for reliability unit commitment
  - Stochastic demand, 100 scenarios
- Extensive form
  - CPLEX, after 1 day of CPU on a 16-core workstation
    - No feasible incumbent solution
- PH, 20 iterations, post-EF solve - serial
  - ~14 hours, 2.5% optimality gap
- PH, 20 iterations, post-EF solve – parallel
  - ~15 minutes, 2.5% optimality gap
- PH, 20 iterations, post-EF solve – parallel with bundling
  - ~15 minutes, 1.5% optimality gap

# Scenario sampling: How many is enough?

- Discretization of the scenario space is "standard" in stochastic programming
  - Often, no mention of solution or objective stability
  - Let alone rigorous statistical hypothesis-testing of stability
  - *Don't trust anyone who doesn't show you a confidence interval*
- Various approaches / alternatives in the literature
  - We like the Multiple Replication Procedure (MRP) introduced by Mak, Morton, and Wood (1999)
- Formal question we are concerned with
  - What is the probability that $\hat{x}$'s objective function value is suboptimal by more than $\alpha$%?
  - But making do with a fixed set or "universe" or scenarios

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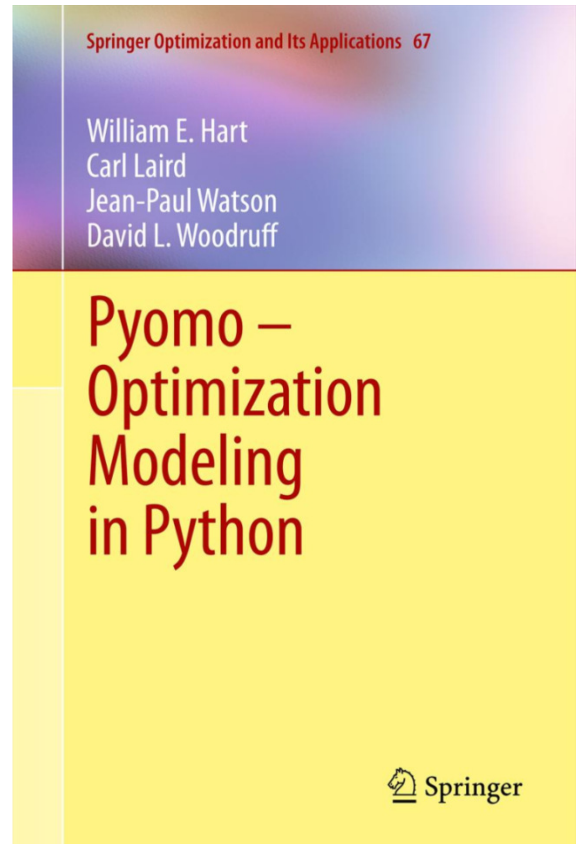
# Our software environment: Coopr

- Project homepage
  - http://software.sandia.gov/coopr
- Poster
- "The Book"




- *Mathematical Programming Computation* papers
  - Pyomo: Modeling and Solving Mathematical Programs in Python (Vol. 3, No. 3, 2011)
  - PySP: Modeling and Solving Stochastic Programs in Python (Vol. 4, No. 2, 2012)

# Our hardware environments

- Our objective is to run on commodity clusters
  - Utilities don't have, and don't want, supercomputers
  - But they do or might have multi-hundred node clusters

- Sandia Red Sky (Unclassified Segment) – 39$^{th}$ fastest on TOP500
  - Sun X6275 blades
  - 2816 dual socket / quad core nodes (22,528 cores)
    - 2.93 GHz Nehalem X5570 processors
    - 12 GB RAM per compute node (1.5 GB per core) << IMPORTANT!
  - For us, the interconnection is largely irrelevant
  - Red Hat Linux (RHEL 5)

- Sandia Red Mesa (with NREL)
  - Similar to Red Sky, but dedicated for energy research

# Conclusions

- Stochastic unit commitment has been studied in the literature
  - Indications are that it holds promise
  - Computational challenges have prevented industrial adoption
  - Far easier on paper and in academia than in practice…
- Our objective is to develop scalable solutions to stochastic unit commitment
  - In tractable run-times
  - On ISO-scale systems
  - To demonstrate (or not) both practical deployment ability and cost savings
  - Using reasonable, high-accuracy stochastic process models *to reduce the number of scenarios while maintaining solution quality*
- We are happy to talk to ISOs, vendors, and academics working toward related goals

# QUESTIONS