40 Years: Energy and Quality of Life
Sustainability is the defining challenge

- Buildings in U.S.  
  - 41% of primary energy/carbon, 73% of electricity, 34% of gas

- Buildings in China  
  - 60% of urban building floor space in 2030 has yet to be built

- Buildings in India  
  - 67% of all building floor space in 2030 has yet to be built
Energy Consumption and Production

TN 2012 Electric Bill - $1,533
Presentation summary

• Uncertainty Quantification
• Autotune
• Trinity Tests
• Results
Presentation summary

• Uncertainty Quantification
• Autotune
• Trinity Tests
• Results
From Visual Analytics and Simulations To Actualized Energy Savings in the Marketplace

- Titan is the world’s #1 fastest buildings energy model simulator
- 500,000+ EnergyPlus building simulations in less than an hour
- 125.1 million U.S. buildings could be simulated in 2 weeks
- 8 million simulations for DOE ref. buildings

- Publicly available resource
## 20 Inputs Sampled

<table>
<thead>
<tr>
<th>Class</th>
<th>Name</th>
<th>Short Name</th>
<th>Field</th>
<th>Default</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lights</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>back_space_lights</td>
<td>Li_BaSp</td>
<td>Field 6</td>
<td>9</td>
<td>6.3</td>
<td>11.7</td>
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<tr>
<td></td>
<td>Core_Retail_lights</td>
<td>Li_CoRt</td>
<td>Field 4</td>
<td>18.5</td>
<td>12.95</td>
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<td>24.05</td>
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<td>point_of_sale_lights</td>
<td>Li_POS</td>
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<tr>
<td><strong>Electric Equipment</strong></td>
<td>BackSpace_MiscPlug</td>
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<td>2.31</td>
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<td>3.3</td>
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<td>Field 6</td>
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<td><strong>ZoneInfil: FlowRate</strong></td>
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<td>ZF_BaSp</td>
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<td>0.00023</td>
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<tr>
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<td>Field 6</td>
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<td>0.00023</td>
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<td>1.625</td>
</tr>
</tbody>
</table>
Sensitivity analysis

- 20 factors, all 2-way interactions discoverable with 1024 simulations (778 degrees of freedom left for the error term)
Sensitivity analysis

• Individual effects on any output
156 inputs effect on 96 outputs
### Determine inputs to calibrate

<table>
<thead>
<tr>
<th>Class</th>
<th>Object</th>
<th>Field</th>
<th>Default</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Distribution</th>
<th>Type</th>
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<th>Constraint</th>
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<tr>
<td>Lights</td>
<td>Bakery_Lights</td>
<td>Watts per Zone</td>
<td>18.29</td>
<td>12.803</td>
<td>23.777</td>
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<td>float</td>
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<tr>
<td>Lights</td>
<td>Deli_Lights</td>
<td>Watts per Zone</td>
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<td>12.803</td>
<td>23.777</td>
<td>uniform</td>
<td>float</td>
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<td>ElectricEquipment</td>
<td>Bakery_MiscPlug_EcDesignLevel</td>
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<td>14617.2</td>
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<tr>
<td>ElectricEquipment</td>
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<td>Design Level</td>
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<td>Bakery_MiscGas_Equipment</td>
<td>Design Level</td>
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<td>GasEquipment</td>
<td>Bakery_MiscGas_Equipment</td>
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<td>ExteriorFacadeLightDesignLevel</td>
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<td>9503.9</td>
<td>17650.1</td>
<td>uniform</td>
<td>float</td>
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<td></td>
</tr>
</tbody>
</table>

Determine inputs to calibrate
MLSuite example

- EnergyPlus – 2-10 mins for an annual simulation

- ~E+ - 4 seconds AI agent as surrogate model, 90x speedup, small error, brittle
Presentation summary

• Uncertainty Quantification
• Autotune
• Trinity Tests
• Results
Existing tools for retrofit optimization

API
OpenStudio
Simulation Engine
DOE–$65M (1995–?)

ASHRAE G14 Requires

Using Monthly utility data
- CV(RMSE) 15%
- NMBE 5%

Using Hourly utility data
- CV(RMSE) 30%
- NMBE 10%

3,000+ building survey, 23-97% monthly error
Autotune
Automatic Calibration of Simulation to Data

EnergyPlus

Easy Input Model
The search problem

Problem/Opportunity:
~3000 parameters per E+ input file

2 minutes per simulation = 83 hours
**ORNL High Performance Computing Resources**

Nautilus: 1024 cores
4TB shared-memory

Kraken: 112,896 cores

Gordon: 12,608 cores
SSD

Titan: 299,008 CPU cores
18,688 GPU cores
710TB memory, distributed

Jaguar: 224,256 cores
360TB memory
### Computational complexity

**Problems/Opportunities:**
- Domain experts chose to vary 156
- Brute-force = $5 \times 10^{52}$ simulations

**E+ parameters**

<table>
<thead>
<tr>
<th>HP1_in_Tot</th>
<th>None_Tot</th>
<th>HP1_out_Tot</th>
<th>HP1_back_Tot</th>
<th>HP1_comp_Tot</th>
<th>HP2_in_Tot</th>
<th>HP2_out_Tot</th>
<th>HP2_back_Tot</th>
<th>HP2_comp_Tot</th>
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<td>6.75</td>
<td>18.75</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**LoKU**
- 13.75 billion years
- Need $4.1 \times 10^{28}$ LoKU
MLSuite: HPC-enabled suite of machine learning algorithms

- Linear Regression
- Feedforward Neural Network
- Support Vector Machine Regression
- Non-Linear Regression
- K-Means with Local Models
- Gaussian Mixture Model with Local Models
- Self-Organizing Map with Local Models
- Regression Tree (using Information Gain)
- Time Modeling with Local Models
- Recurrent Neural Networks
- Genetic Algorithms
- Ensemble Learning

Acknowledgment: UTK computer science graduate Richard Edwards, Ph.D. (advisor Dr. Lynne Parker); now Amazon
MLSuite Architecture

Data Preparation

30x LS-SVMs
validation folds 1-10
input orders 1-3
MLSuite: HPC-enabled Suite of Machine Learning algorithms

- Linear regression
- Feedforward neural network
- Recurrent neural networks
- Support vector machine regression
- Non-linear regression
- Gaussian mixture model with local models
- Self-organizing map
- Kernel Ridge Regression

- Bayesian calibration
- Markov blankets
- Regression tree (using information gain)
- Time modeling with local models
- K-means with local models
- Genetic algorithms
- Ensemble learning
<table>
<thead>
<tr>
<th></th>
<th>Thickness</th>
<th>Conductivity</th>
<th>Density</th>
<th>Specific Heat</th>
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</thead>
<tbody>
<tr>
<td>Bldg1</td>
<td>0.022</td>
<td>0.031</td>
<td>29.2</td>
<td>1647.3</td>
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<tr>
<td>Bldg2</td>
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<td>0.025</td>
<td>34.3</td>
<td>1402.5</td>
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<td>(1+2)_1</td>
<td>0.0229</td>
<td>0.029</td>
<td>34.13</td>
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<tr>
<td>(1+2)_2</td>
<td>0.0262</td>
<td>0.024</td>
<td>26.72</td>
<td>1502.9</td>
</tr>
</tbody>
</table>

Evolutionary computation

How are offspring produced?

- Average each component
- Add Gaussian noise
- “AI inside of AI”
Getting more for less

- EnergyPlus is slow
  - Full-year schedule
  - 2 minutes per simulation

- Use abbreviated 4-day schedule instead
  - Jan 1, Apr 1, Aug 1, Nov 1
  - 10 – 20 seconds per simulation

Monthly Electrical Usage: $r = 0.94$
Hourly Electrical Usage: $r = 0.96$
Evolutionary combination
Autotune Calibrates Building Energy Models

Leveraging HPC resources to calibrate models for optimized building efficiency decisions

**Features:**
- Calibrate any model to data
- EnergyPlus calibrated in 1 hour (web service) or 6 hours (laptop)
- Calibrates to the data you have (monthly utility bills to submetering)

**Results:**

<table>
<thead>
<tr>
<th></th>
<th>Monthly utility data</th>
<th>Hourly utility data</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVR</td>
<td>15%</td>
<td>30%</td>
</tr>
<tr>
<td>NMBE</td>
<td>5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Results of 24 Autotune calibrations (3 types, 8, 34, 79 tuned inputs each)

<table>
<thead>
<tr>
<th>Residential home</th>
<th>Tuned input avg. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within 30¢/day (actual use $4.97/day)</td>
<td>Hourly – 8% Monthly – 15%</td>
</tr>
</tbody>
</table>

20+ organizations interested
Presentation summary

• Uncertainty Quantification
• Autotune
• Trinity Tests
• Results
Trinity Test

• System implements BESTEST-EX’s “pure calibration”
Trinity Test Availability


- Works only with EnergyPlus 7.0
- Doesn’t capture sensor drift/miscalibration
- Doesn’t capture gap between physics and simulation
- Python script converts IDD to XSD
  - Converts CSV+IDF to XML
  - Converts XML to CSV+IDF
Presentation summary

• Uncertainty Quantification
• Autotune
• Trinity Tests
• Results
HPC-informed algorithmic reduction... to commodity hardware

LoKU 13.75 billion years

Need $4.1 \times 10^{28}$ LoKU

1 hour
That’s great, but how can I use it?
Provide actual data

Select location
Current Selection: Chicago, IL

Input Data

Electricity

Have a file containing energy usage:
Choose File: No file chosen
Sample File: Monthly Sample, Hourly Sample
OR

Energy usage from previous months:

January
Energy Usage kWh

February
Energy Usage kWh

March
Energy Usage kWh

April
Energy Usage kWh

May
Energy Usage kWh

June
Energy Usage kWh

July
Energy Usage kWh

August
Energy Usage kWh

September
Energy Usage kWh

October
Energy Usage kWh

November
Energy Usage kWh

December
Energy Usage kWh

Gas

Temperature

Tune

You have completed all the steps of the wizard!

Click Tune below to Submit your Information

Email Address (optional):
## Autotune returns calibrated model

### Input Error Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input error average</td>
<td>24.38</td>
</tr>
<tr>
<td>Input error maximum</td>
<td>66.12</td>
</tr>
<tr>
<td>Input error minimum</td>
<td>0.09</td>
</tr>
<tr>
<td>Input error variance</td>
<td>228.53</td>
</tr>
</tbody>
</table>

### CV(RMSE)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4:Facility <a href="Monthly">kg</a></td>
<td>9.95</td>
</tr>
<tr>
<td>CO2:Facility <a href="Monthly">kg</a></td>
<td>15.42</td>
</tr>
<tr>
<td>CO:Facility <a href="Monthly">kg</a></td>
<td>20.40</td>
</tr>
<tr>
<td>Carbon Equivalent:Facility <a href="Monthly">kg</a></td>
<td>14.42</td>
</tr>
<tr>
<td>Cooling:Electricity <a href="Hourly">J</a></td>
<td>1577.96</td>
</tr>
<tr>
<td>Electricity:Facility <a href="Hourly">J</a></td>
<td>10.48</td>
</tr>
</tbody>
</table>

### NMBE

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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<tbody>
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<td>CH4:Facility <a href="Monthly">kg</a></td>
<td>-9.57</td>
</tr>
<tr>
<td>CO2:Facility <a href="Monthly">kg</a></td>
<td>-14.78</td>
</tr>
<tr>
<td>CO:Facility <a href="Monthly">kg</a></td>
<td>-19.52</td>
</tr>
<tr>
<td>Carbon Equivalent:Facility <a href="Monthly">kg</a></td>
<td>-13.83</td>
</tr>
<tr>
<td>Cooling:Electricity <a href="Hourly">J</a></td>
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<tr>
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<td>-9.52</td>
</tr>
<tr>
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</table>

### 143+ outputs

```
<Material>
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  <Roughness>Smooth</Roughness>
  <Thickness tuneType="float"
    tuneMin="0" tuneMax="0.5"
    tuneDistribution="uniform"
    tuneGroup="A"
    tuneConstraint="A+B\lt;1">0.005</Thickness>
</Material>
```

IDF + CSV = XML

Autotune returns calibrated model.
## Autotune Performance

<table>
<thead>
<tr>
<th></th>
<th>ASHRAE G14 Requires</th>
<th>Autotune Results</th>
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<tbody>
<tr>
<td><strong>Monthly utility data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVR</td>
<td>15%</td>
<td>0.32%</td>
</tr>
<tr>
<td>NMBE</td>
<td>5%</td>
<td>0.06%</td>
</tr>
<tr>
<td><strong>Hourly utility data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVR</td>
<td>30%</td>
<td>0.48%</td>
</tr>
<tr>
<td>NMBE</td>
<td>10%</td>
<td>0.07%</td>
</tr>
</tbody>
</table>

Results from 24 Autotune calibrations (3 building types - 8, 34, 79 tuned inputs each)

- Hourly – 8%
- Monthly – 15%

Input-side Error
Autotune Availability

BAD NEWS
FY15 project to integrate Autotune with OpenStudio for cloud-based calibration is on hold indefinitely

GOOD NEWS
Autotune has been open-sourced and is freely available at https://github.com/ORNL-BTRIC/Autotune
- Backend – does all the work
- Service – web service API
- Frontend – website
Discussion

Oak Ridge National Laboratory

Joshua New, Ph.D.
newjr@ornl.gov