High Performance Buildings:
*Measures, Complexity, Current Trends*

Bryan Eisenhower

*Associate Director*
Center for Energy Efficient Design
*Researcher*
Department of Mechanical Engineering
UCSB

INORGANIC MATERIALS FOR ENERGY
CONVERSION AND STORAGE
August 23, 2012
Buildings are everywhere
Buildings are important
Buildings are challenging
High Performance Buildings: Measures, Complexity, Current Trends

Primary focus:
Large Commercial buildings
Equipment operation inside of them
In the United States

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INORGANIC MATERIALS FOR ENERGY CONVERSION AND STORAGE
August 23, 2012
Measuring building performance usually combines different metrics into a ratio. Some examples below:

**Numerator**
- Energy consumption / $
- Peak Load / $
- Energy emissions
- % Renewable
- Change year / year
- Carbon footprint
- Embodied energy
- Global warming potential
- Indoor air quality
- ....

**Denominator**
- Per Square foot
- Per visit (e.g. storefront)
- Per transaction
- Per academic degree
- Per lecture hour
- Thermal comfort (measured)
- Observed comfort (survey)
- Number of service calls
- ....

* The num/den can be flipped

This balance is dependent upon ‘building type’
Largest players:
Education, Mercantile, Office, Warehouse
Measuring Performance

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Measuring Performance

- Energy Costs
- Thermal Comfort
Energy Use

Estimated U.S. Energy Use in 2010: ~98.0 Quads

- Solar: 0.11
- Nuclear: 8.44
- Hydro: 2.51
- Wind: 0.92
- Geothermal: 0.21
- Natural Gas
- Coal: 20.82
- Petroleum: 35.97
- Biomass: 4.29
- Renewable: 17%
- Net Electricity Imports: 0.09
- Electricity Generation: 39.49
- 40% For Buildings
- 57% Wasted
- Rejected Energy: 56.13

Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527
Motivation

- No drastic changes in time!
- Major portions of energy consumption in buildings is driven by controls.

We can influence this.
Energy Peak Demand

- Power grid design constraints based on \textit{max} loading, which occurs very \textit{infrequently}.

Only used 10 days a year…

- Southern CA Edison Data: CA OASIS
  - Top 25% of power only \(2.74\%\) of year.

- UCSB Building Data
  - Top 25% of power only \(0.41\%\) of year.
The easy solution to the energy problem is to ‘turn the building off’
- The easy solution to the energy problem is to ‘turn the building off’
- Comfort is needed to:
  - Produce results
  - Earn degrees
  - Sell products
  - Heal people (hospitals)
  -...

Approximate breakdown of building expenses

- Salaries: 84%
- Rent: 14%
- Energy: 1%
- Repair & Maintenance: 1%

Sources: Cleret al. (1997), Sheehy (2009) / CMU
Thermal Comfort

Factors influencing thermal comfort:
- Metabolic rate
- Clothing
- Air temperature
- Radiant temperature
- Humidity
- Air speed

Source: ASHRAE STD55-2004
Calculating Comfort

Graph-based

Graphical method with met 1.0-1.3 (office environment)

Fanger 1970’s:

\[
PMV = (0.303e^{-0.036M} + 0.028)L
\]

\(M\) = metabolic rate
\(L\) = Human heat balance

* Note that even with a PMV of 0.0, about %5 of people will be uncomfortable

Source: ASHRAE STD55-2004
Measuring Performance

Energy Costs

Thermal Comfort
- Designing and equipping buildings is like a puzzle
- There are few products with as much hand-built and expert-experience involved in their production
- Nearly all buildings are one-off designs pulling together different pieces / design elements to form the puzzle
Architecture

Equipment
Architectural aspects in building design
Building orientation can be optimized based on climate and location.
Envelopes

- Constructions
- Shading
- Fenestration
The balance between internal loads (e.g. people, computers, lights) and exterior climate dictates amount of isolation desired between occupants and outdoors.

Typically high degree of isolation is sought after through the use of insulation (e.g. R21 etc.).

Many different types of insulation and material layering design have been used.

The quality of the surface has impact on what occupants feel (think radiation and surface conduction to internal mass).
Internal mass has significant influence on dynamics of the building.

Concrete vs. wood impacts the time distribution and storage of heat.

Examples:
- Night cooling with ventilation to store cool energy in walls for next day
- Pushing mid-day heat to after-work hours

Energy and Environment in Architecture, Baker
Envelope

- Constructions
- Shading
- Fenestration

Shading:

- Manmade or natural approaches
- Internal or external devices
- Automatically adjusted
- Designed for different seasons

Energy and Environment in Architecture, Baker
Windows offer visual occupant comfort, free light – at the cost of heat loss/gain

- Low-emissivity coatings
- Boundary layer stacking (e.g. double pane)
- Spectrally selective glass
- Low conduction / leakage designs (frame)
- Switchable glazing
Equipment

- Lighting
- Ventilation
- Heating
- Cooling
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

- Natural light harvesting can be achieved with low solar heat gain using various approaches

- High performance electrical lighting is hot topic

- Other approaches: auto dimming, or occupancy based, task lighting, etc.

**Light Shelf**

Fundamentals of Sustainable Dwellings, Friedman
Ventilation needed for indoor air quality

Typically measured by Air Changes per Hour (ACH)

<table>
<thead>
<tr>
<th>Environment</th>
<th>Rec. ACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td>4-6</td>
</tr>
<tr>
<td>Bar / Dining</td>
<td>12-30</td>
</tr>
<tr>
<td>Kitchens</td>
<td>15-60</td>
</tr>
<tr>
<td>Class 1 Clean room</td>
<td>~600</td>
</tr>
</tbody>
</table>

Leakage can account for .5-10 ACH depending on construction, wind, inside pressures, occupant behavior.
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

Natural Ventilation
Has been used since ancient times

Works best in mild climates and tall buildings

Dependent on buoyancy and pressure gradients (wind)

Can be automated with louvers, operable windows

1844 Prison design achieved 3 ACH without fans

Automated louvers @ UCSB Student Resources Building
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

Ducted Ventilation
Typical modern approach that distributes conditioned air (from the roof units) throughout the building.

ACH can be dialed in fairly closely, including recirculating air to save energy.

Management systems allow scheduling to throttle back flows for un-occupied hours.

Nighttime flush/ventilation an effective strategy.
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

Ducted Ventilation
Single duct must use terminal reheat to satisfy different types of zones

Dual duct mixes hot and cold temperatures to achieve desired conditions

Choosing hot and cold temperatures or supply temperatures is an optimization problem

Either system can have variable or constant flow rates

Un-ducted ventilation through underfloor distribution
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

Heating can be obtained by passive measures including capturing solar energy.

Energy intensive sources:
- Boiler
- District heating
- Heat pump
- Electric
- ....

Trombe wall captures solar radiation.
Cooling can be achieved by similar methods (e.g. chiller machines)

Chilled water distributed through piping throughout the building / district

Water goes through heat exchangers with air, chilled beams, etc.
Equipment

- Lighting
- Ventilation
- Heating
- Cooling

Some advanced technologies include ground source cooling (air or heat pump)

Phase change materials

Phase change materials store energy for later times

Ground source heat pumps, ducting gets free energy from ground

Fundamentals of Sustainable Buildings, Friedman

Phase change materials store energy for later times

specialtyfabricsreview
- Designing and equipping buildings is like a puzzle
- There are few products with as much hand-built and expert-experience involved in their production
- Nearly all buildings are one-off designs pulling together different pieces / design elements to form the puzzle
Can it be done?

9/11/2002
Ed Mazria’s challenge to get companies, govt, product manufactures to make Carbon Neutral Buildings by 2030

**Initiatives**

![2030 Architecture Initiative](image)

**The 2030 Challenge**

<table>
<thead>
<tr>
<th>Year</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>TODAY</td>
<td>60%</td>
</tr>
<tr>
<td>2015</td>
<td>70%</td>
</tr>
<tr>
<td>2020</td>
<td>80%</td>
</tr>
<tr>
<td>2025</td>
<td>90%</td>
</tr>
<tr>
<td>2030</td>
<td>CARBON NEUTRAL*</td>
</tr>
</tbody>
</table>

*Using no fossil fuel GHG-emitting energy to operate.

**US: $25 Billion funding for energy efficiency (not solely buildings) 2009**

**DOE Recovery Awards**

- **Carbon Capture and Storage**
- **Renewable Energy**
- **Science and Innovation**
- **Transportation**
- **Energy Efficiency**
- **Modernizing the Grid**

**DOE Recovery Act Field Projects**

- **United States**
- **Mexico**
- **Canada**
Examples

- It can be done! *(1-off examples)*

**A Grander View**, Ontario Canada
- 22Kft^2 office
- **80% Energy savings** as recorded in first year
- Most energy efficient office in CA

**David Brower Center**, Ontario Canada
- 45Kft^2 office / group meetings
- **42.4% Energy savings** as recorded in 11 months.

**The Energy Lab**, Kamuela Hawaii
- 5.9Kft^2 Educational
- **75% Energy savings** compared to CBECS
- 1st year generated 2x electricity that it used
Pitfalls


Pitfalls

➢ “….these strategies must be applied together and properly integrated in the design and operation to realize energy savings. There is no single efficiency measure or checklist of measures to achieve low-energy buildings. “

➢ “… dramatic improvement in performance with monitoring and correcting some problem areas identified by the metering “

➢ “There was often a lack of control software or appropriate control logic to allow the technologies to work well together “


[Frankel 2008]
Thermal Zone
Fresh Air
Outdoors

Thermal Zone

Fresh Air
Systems - of - Systems

- Fresh Air
- Hot Water
- Chilled water
- Refrigerant

Thermal Zone
Outdoors
Systems - of - Systems

Outdoors

- Fresh Air
- Hot Water
- Chilled water
- Refrigerant
- Cooling Tower

Thermal Zone
Systems - of - Systems

- Fresh Air
- Hot Water
- Chilled water
- Refrigerant
- Cooling Tower
- Controllers

Thermal Zone

Outdoors
Numerous zones in a single building

Loops operate at different time scales

Loops are spread through different spatial scales

Stochastic disturbance on every system

Heterogeneous media (water, air, refrigerant)

Heterogeneous manufacturers / protocols
Modeling

Data

Control
Energy Modeling - Choices

Whole-building simulation, used for design and compliance
Just broke < 1 hour resolution in past 10 yrs.

Component / zone level modeling for one-off detailed studies or control analysis, model predictive control …
Energy Modeling – Uses

Reasons for modeling (entire building)

- Compliance
  - Leadership in Energy and Environmental Design (LEED)
  - ASHRAE
  - Rebates (tax) for efficient design

- Design trades
  - Usually very few performed in design firm

- Academic Studies
  - Prediction of un-sensed data
  - Uncertainty / Sensitivity Analysis
  - Optimization (design / operation)
  - Optimal control
  - ....
Decades spent on developing energy models

- Most are validated on a component basis.

At the systems level, the most advanced energy models are still not accurate during the design stage.

![Comparison (With Process Loads)](attachment:image)

* Stanford Y2E2 Building
The general idea is to take many realizations of the model, quantify how changes in the model influence changes in the output and identify which are the critical parameters and use this info. for analysis.
Create Energy Model
E+, TRNSYS, Modelica

Identify uncertain parameters, perform sampling
All numerical design & operation scenario (DOS) parameters in the model are varied concurrently (not architectural design).

- Parameters are varied 30% of their mean.
- Some parameters are of the form $a+b < 1$.

Number of parameters are in the 1000’s for a typical building design.

Traditional analysis approaches are not scalable!
Parameter Sampling

- Monte-Carlo (random) = clumps
- Deterministic = uniformly ergodic
Convergence Properties

- Monte Carlo bound $\sim \frac{1}{\sqrt{N}}$
- Deterministic bound $\sim \frac{1}{N}$

Faster convergence means more parameters can be studied in the same amount of time!

Biggest difference between MC & Deterministic is when $N$ is large

2 orders of magnitude in problem size achieved with respect to past literature
Create Energy Model E+, TRNSYS, Modelica

Identify uncertain parameters, perform sampling

Perform numerous simulations, pre-process output
**Typical Output Distributions**

<table>
<thead>
<tr>
<th>Facility and Submetered Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Comfort</td>
</tr>
<tr>
<td>+ Gas Facility</td>
</tr>
<tr>
<td>+ Electricity Facility</td>
</tr>
<tr>
<td>Thermal Comfort</td>
</tr>
<tr>
<td>Heating</td>
</tr>
<tr>
<td>Cooling</td>
</tr>
<tr>
<td>Pump</td>
</tr>
<tr>
<td>Fan</td>
</tr>
<tr>
<td>Interior Lighting</td>
</tr>
<tr>
<td>Interior Equipment</td>
</tr>
</tbody>
</table>

- 5000-6000 realizations performed to obtain convergence
- The ‘control’ mechanisms in the model drive distributions towards Gaussian although others exist as well

* TRNSYS results
Characteristics of the output based on different inputs

Influence of Different Parameter Variation size

Input Uncertainty @ 10%

Input Uncertainty @ 20%
Characteristics of the output are considered based on different designs.

Nominal vs. High Efficiency Design

![Graphs showing comparisons between Nominal and High Efficiency Designs](image)

Uncertain Inputs

![Building Model](image)

Uncertain Outputs

![Bar charts showing standard deviations](image)
Detailed Whole-Building Model

Analytic Linear Meta-model

Uncertainty in closed loop performance

771 Physical parameters with uncertain bounds

\[ C \frac{dT}{dt} = \sum_{i=1}^{N_{\text{faces}}} \dot{Q}_{\text{conv},i} + \sum_{i=1}^{N_{\text{mags}}} \dot{Q}_{\text{magn},i} + \sum_{i=1}^{N_{\text{tel}}} \dot{Q}_{\text{elec},i} + \dot{Q}_{\text{HVAC}}. \]

\[ \dot{x} = A(x_0, p)x + B_u(x_0)u + B_w(x_0, p)w \]

\[ y = Cx \]

Eisenhower, et al. EXTRACTING DYNAMIC INFORMATION FROM WHOLE-BUILDING ENERGY MODELS, ASME Design for Dynamics 2012
Sensitivity Analysis

Uncertainty Quantification

Uncertain Inputs

Building Model

Uncertain Outputs

$\gamma(1000)$

$\gamma(10)$
Sensitivity Analysis

Uncertainty Quantification

Uncertain Inputs

Building Model

Uncertain Outputs

Sensitivity Analysis
Identifying key parameters in a building helps in design optimization, continuous commissioning, model calibration, ...

Typically only a few parameters drive uncertainty in output.

Hand calibration from SA

Modeling and Calibration of Energy Models for a DoD Building
ASHRAE Annual Conference, Montreal 2011
Identify uncertain parameters, perform sampling

Perform numerous simulations, preprocess output

Calculate full order meta-model

Create Energy Model E+, TRNSYS, Modelica
Machine Learning / Regression

- Identify characteristics within data without prior knowledge of the regressors
- Applications: object detection, classification of biological data, speech or image recognition, internet or database searching.....
- Soft margin set up to identify outliers....

Smola [2004]

Principle of Support Vector Machines (SVM)

Input Space

Feature Space

http://www.imtech.res.in/raghava/rbpred/svm.jpg

Machine learner

A *model of a model* (meta-model) is created to provide means for analytic assessment of building energy & comfort predictions. Structure of the model is similar to the full order energy model, *not a line fit to the data*.  

- 2063 inputs, 2 outputs
Create Energy Model E+, TRNSYS, Modelica

Identify uncertain parameters, perform sampling

Perform numerous simulations, pre-process output

Calculate full order meta-model

Perform UQ/SA

Calibration

Optimization

FMEA

Model Reduction
Optimization

\[
\begin{align*}
\text{Min } & \quad F(x, Y, Y') \\
\text{Subject to:} & \\
& g_i(x) = 0 \quad i = 1, \ldots, m \\
& h_j(x) \leq 0 \quad j = 1, \ldots, n
\end{align*}
\]
Objectives in buildings are naturally competitive.
Objectives in buildings are naturally competitive

Many whole-building energy simulators do not lend themselves well to optimization

Function evaluations take a long time

Evaluations may get stuck at local minima
Create Energy Model
E+, TRNSYS, Modelica

Identify uncertain parameters, perform sampling

Perform numerous simulations, pre-process output

Calculate full order meta-model

Perform UQ/SA

Rapid function evaluations allow 2x order of magnitude more parameters
45% annual energy reduction while increasing comfort by a factor of two.

Model reduction based on parameter type or parameter influence

Rank ordering of parameter sensitivity

Parameters collected by type

Model Calibration
Calibration approach tested on DOD Building 26
Data available 2009, 2010, some 2011:
- Plug electricity
- Total electricity
- Steam consumption

Optimization performed to minimize $\sqrt{\sum (\text{model} - \text{data})^2}$

Per month, year, etc.

Rank order critical parameters
Assimilate model using output constraints
Calibration approach tested on DOD Building 26
Data available 2009, 2010, some 2011:

- Plug electricity
- Total electricity
- Steam consumption

Used for calibration

Optimization performed to minimize \( \sqrt{\sum (\text{model} - \text{data})^2} \)

Per month, year, etc.
model-based

Failure Mode Effect Analysis
## Modeling Failures

### Partial list of types of Failures
- Sensor error
- Flow restriction / leaks
- Motor/impeller failures
- Surface Fouling HEX, Collector
- Stuck valve / dampers
- Improper controller programming
- Inadequate insulation
- Envelope breach
- Shades inoperable
- High internal load

### Distribution of Failure Modes

<table>
<thead>
<tr>
<th></th>
<th>Alarm</th>
<th>Can not Model</th>
<th>Modeled</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope</td>
<td>0</td>
<td>4</td>
<td>52</td>
<td>56</td>
</tr>
<tr>
<td>HVAC Equipment</td>
<td>10</td>
<td>12</td>
<td>74</td>
<td>96</td>
</tr>
<tr>
<td>HVAC Controls</td>
<td>29</td>
<td>160</td>
<td>502</td>
<td>691</td>
</tr>
<tr>
<td>Internal Gains</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Internal Gain Controls</td>
<td>0</td>
<td>1</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>39</strong></td>
<td><strong>177</strong></td>
<td><strong>667</strong></td>
<td><strong>883</strong></td>
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<td></td>
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<td>0%</td>
<td>6%</td>
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<tr>
<td></td>
<td>1%</td>
<td>1%</td>
<td>8%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>3%</td>
<td>18%</td>
<td>57%</td>
<td>78%</td>
</tr>
<tr>
<td></td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>0%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4%</strong></td>
<td><strong>20%</strong></td>
<td><strong>76%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

*This table from Kevin Otto – RSS (see session 9a SIMBUILD 2012)*
Partial list of types of Failures
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</tr>
</tbody>
</table>

*This table from Kevin Otto - RSS*
Uncertainty analysis illustrates impact of multiple failures on building performance

Sensitivity analysis ranks failures based on their impact

<table>
<thead>
<tr>
<th>Output 9: Heating Annual Consumption</th>
<th>Boiler gas/air flow restricted/leaks</th>
<th>AHU2 Economizer OA damper fails open</th>
<th>Zone 7 Thermostat improperly located</th>
<th>Nightsetpoint temperature set incorrectly</th>
<th>Lighting not turned off at night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sensitivity</td>
<td>0.09</td>
<td>0.05</td>
<td>0.81</td>
<td>0.84</td>
<td>1.12</td>
</tr>
<tr>
<td>First Order</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Boiler gas/air flow restricted/leaks</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>AHU2 Economizer OA damper fails open</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>0.67</td>
<td>0.02</td>
</tr>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Data and control are tied together

As of now, control systems in buildings are very decentralized, whole building control not a current approach

This is robust but causes inefficiencies

One goal of current research is to centralize some of the info into aggregates to identify where systems are fighting each other
Typical Sensor Trends
Typical Sensor Trends

Outdoor air temperature

Indoor air temperatures

Amplification or Attenuation

Phase Delay
Movies
Spatial-Frequency Analysis

Sensor Information

$\alpha(1000)$

With I. Mezic UCSB
Spatial-Frequency Analysis

Sensor Information

Engineering Information

$\mathcal{O}(1000)$

$\mathcal{O}(10)$

With I. Mezic UCSB
Spectral Analysis
Spectral decomposition is an approach that isolates spatial energy and temporal energy.

Using operator theoretic methods, we take a finite dimensional nonlinear system and project it onto infinite dimensional linear dynamics.
Koopman Approach

…..Step 1

Original and complicated time domain data
Koopman Approach

…..Step 2

Investigate and choose freq. in Koopman spectrum

Work-day 7-8 hrs

Diurnal
Koopman Approach

Magntitude and phase of Koopman mode quickly illustrates performance

\[
|KM(i)| = 20 \log_{10} \left| \frac{\psi_i}{\psi_{OAT}} \right|
\]

\[
\angle KM(i) = \angle \psi_i - \angle \psi_{OAT}
\]

.....Step 3

Architectural floor plan, first floor
Example: Inefficient Control

- Method quickly isolates sensor / control issues

  Energy at unexpected frequencies

- Cycling found in control system

- System retuned to reduce cycling
Example – Model Tuning

- Comparison between extensive EnergyPlus model and data

**Spectrum**

**Magnitude**

Data

Model

Eisenhower [Simbuild 2010]
Hong Kong: Efficiency analysis*

- One Island East – Westlands Rd. Hong Kong
  - 70 story sky-scraper

- Out-of-phase controller response one heating, one cooling is usually indicative of inefficient operation

* With Walter Yuen, Hong Kong Poly. Univ.
Installed Monitor @ UCSB
Clustering
What are the essential components of a productive network?

Decomposition provides an understanding of essential production units and the pathway energy/information/uncertainty flows through the dynamical system.

Integrated Gasification Combined Cycle, or IGCC, is a technology that turns coal into gas into electricity.
What are the essential components of a productive network?

Decomposition provides an understanding of essential production units and the pathway energy/information/uncertainty flows through the dynamical system.

Integrated Gasification Combined Cycle, or IGCC, is a technology that turns coal into gas into electricity.
Uncertainty at each node and pathway flow identified for a heterogeneous building

Facility Electricity (Total Consumption, Summer Months)

Circles: Uncertainty at each node
Line Thickness: ‘conductance’

Intermediate Consumption Variables

Input Parameter Types

Facility Electricity

Clustering Dynamics

Detailed Whole-Building Model

Detailed Energy Software

Analytic Meta-model
Test case:
Medium office building, 53 kft$^2$, 18 zones

Binary adjacency matrix defined from analytic linearized form of full EnergyPlus model

$\tilde{A} = \frac{1}{2} (A + A^T)$

$W_{Bin} = \begin{cases} 1 & \text{if } A \neq 0 \\ 0 & \text{if } A = 0 \end{cases}$

$L = \text{deg}(W) - W$
Clustering

A matrix of Dynamics in an EnergyPlus model

Uncertainty in spectral gap of the graph Laplacian illustrates robustness of interconnectivity of energy dynamics
Model Predictive Control

Gather Data

Send to building

Evaluate dynamic model

Optimize solution

Base Case

Model based optimization

Model-based control takes into account climate, thermal storage, expected behavior to optimize building

Corbin 2011
Questions?
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Collaborators:
Zheng O’Neill United Technologies Research Center
Satish Narayanan United Technologies Research Center
Shui Yuan United Technologies Research Center
Vladimir Fonoberov AIMdyn Inc.
Kevin Otto RSS
Igor Mezic University of California, Santa Barbara
Michael Georgescu, Erika Eskenazi, Valerie Eacret  UCSB