Big Data Dynamics for Low CAPEX Whole Building Controls

UC SANTA BARBARA
engineering

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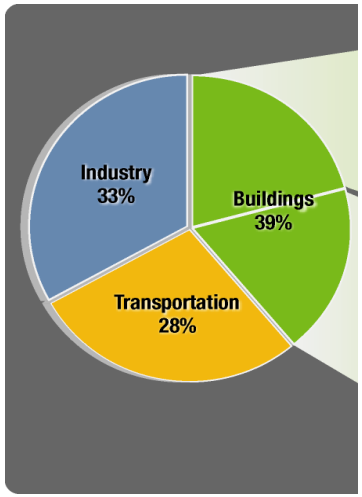
ARPA-E,
Reducing CAPEX for Energy-Efficient Building Controls
October 22, 2014

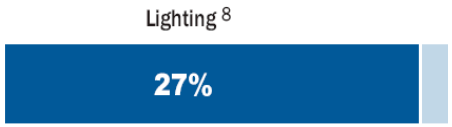
The convergence of research and innovation.

Energy



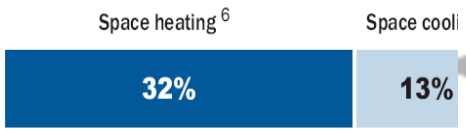
Commercial energy end usage

In 2006 the commercial sector consumed 17.
The category "Other" includes non-building co



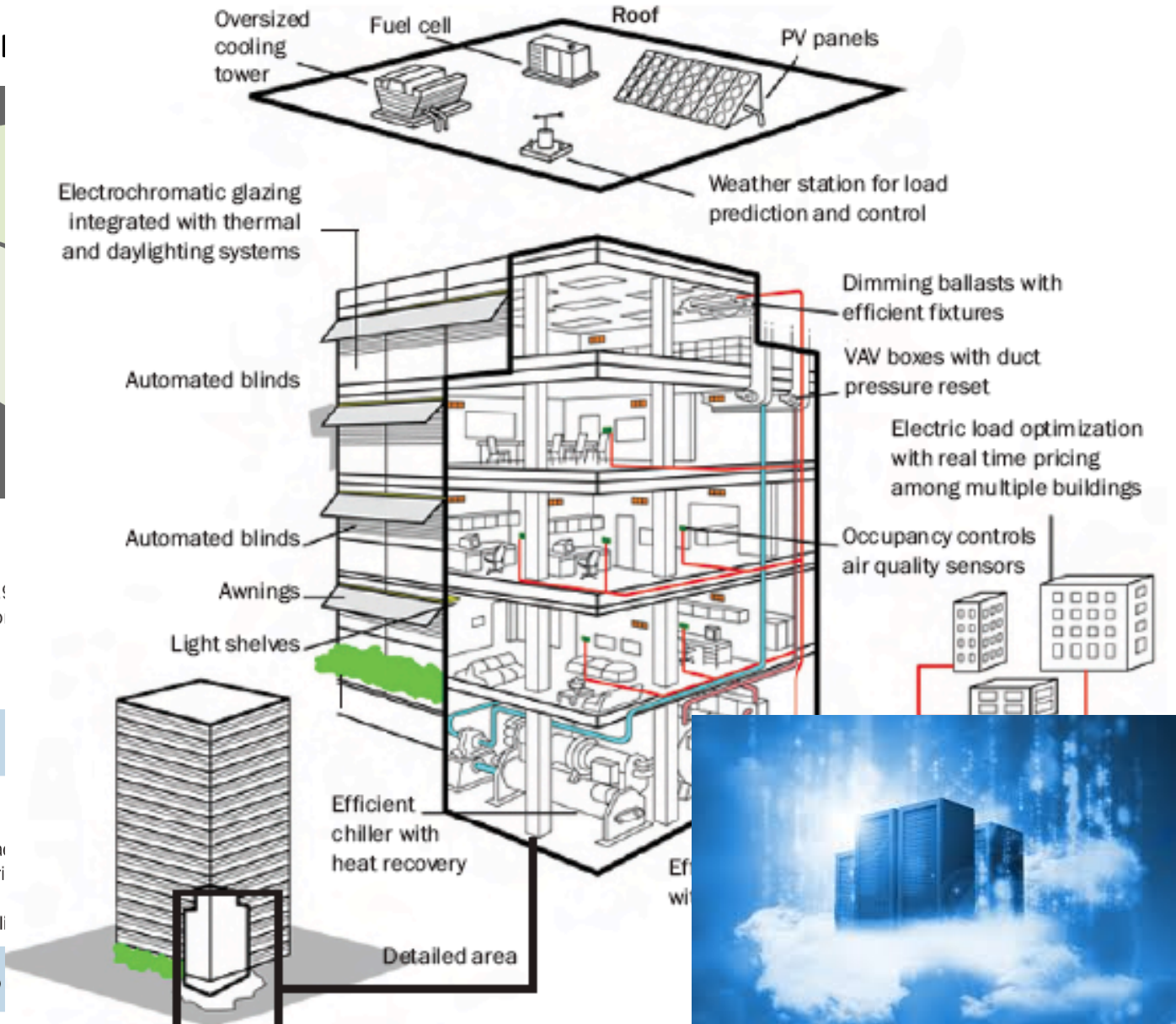
Residential energy end usage

In 2006 the residential sector consumed 21.8 qua
This chart shows the relative amounts going to vari

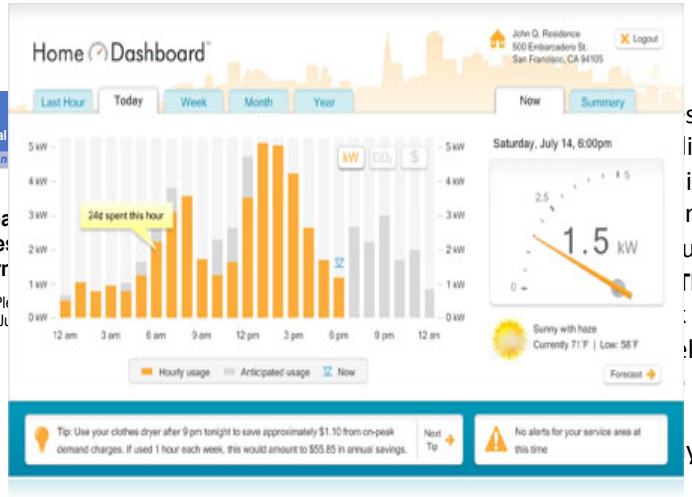


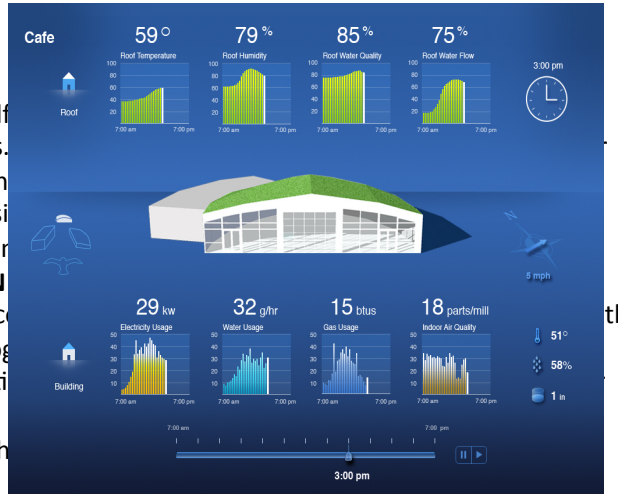
A commercial building with integrated systems design and operations

This diagram of a large commercial building shows various aspects and systems whose interactions are important for optimum building operation and minimum energy consumption.

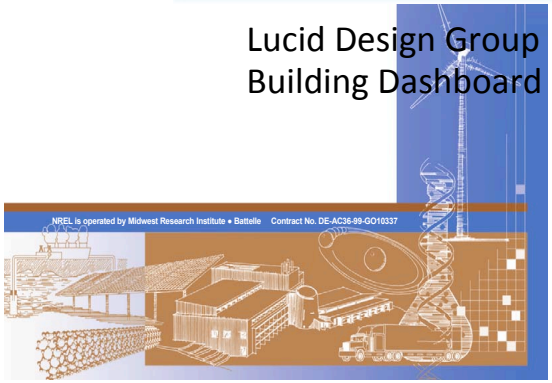


Current Practice





Lucid Design Group Building Dashboard



Agilewaves Building Dashboard

-Plug loads were often greater than design predictions.

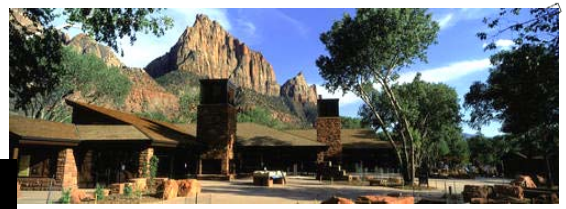
-Effective insulation values are often inflated when comparing the actual building to the asdesigned building.

-PV systems experienced a range of operational performance degradations. Common degradation sources included snow, inverter faults, shading, and parasitic standby losses. “

-NEED INTEGRATED CONTROL SOFTWARE AND UNCERTAINTY ANALYSIS

•Each of these buildings saved energy, with energy use 25% to 70% lower than code. Although each building is a good energy performer, additional energy efficiency and on-site generation is required for these buildings to reach DOE’s ZEB goal.

-NEED FOR FOR ENERGY EFFICIENT DESIGN BLUEPRINTS

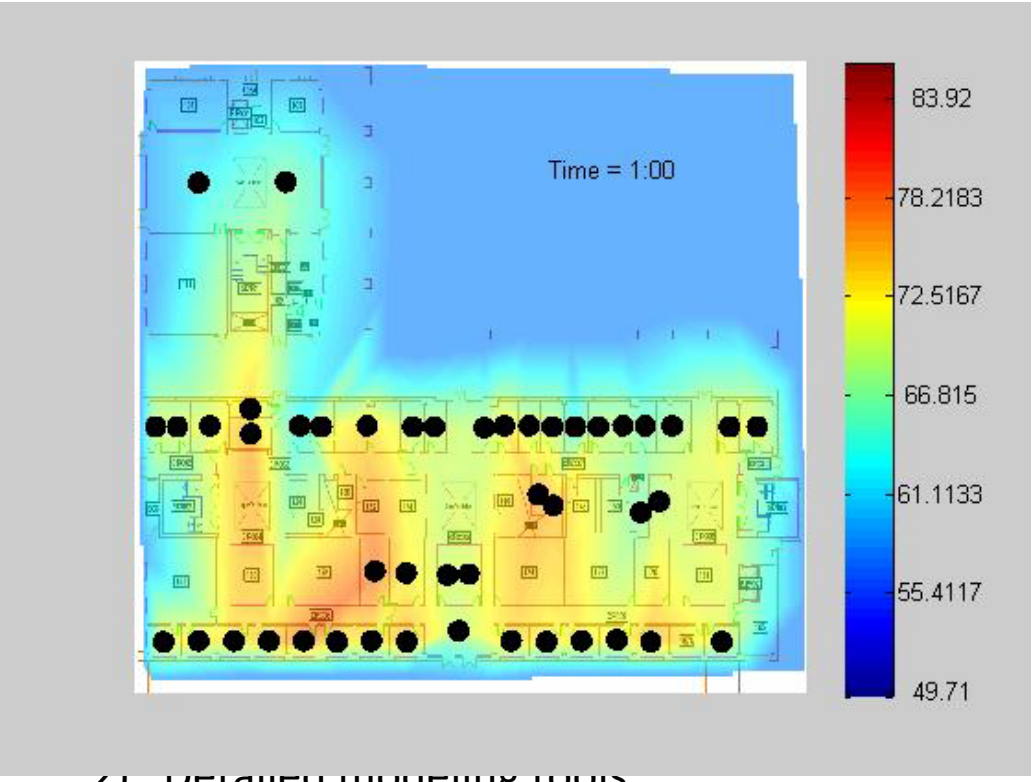


Unique

Cookie-cutter

The Science of It

- **Automatic control problems:**
  1) Given existing systems in a building, keep it operating within comfort range at



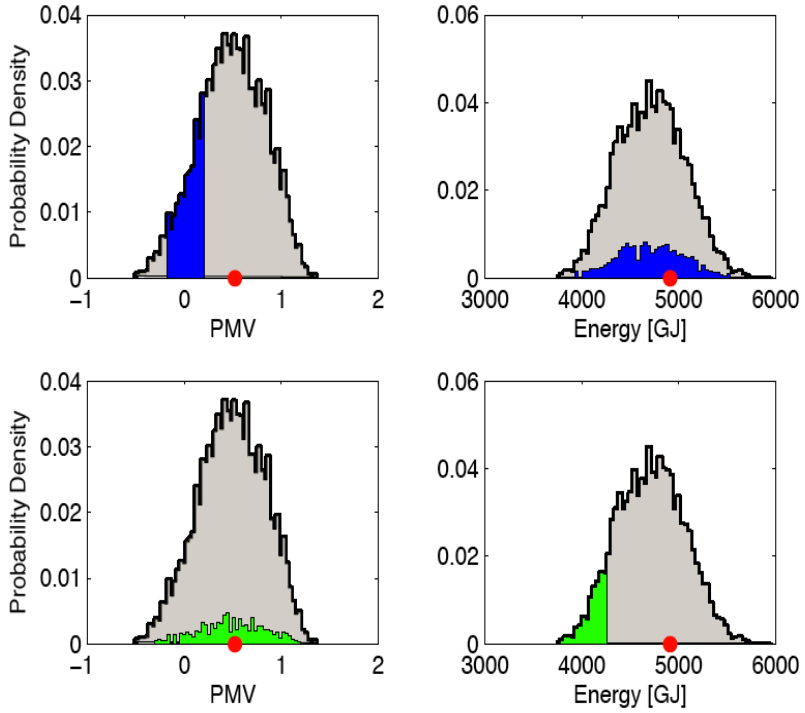


Figure 2: Probability density of both comfort and energy usage for 5000 DOS iterations for a proposed building DOS. In the upper row, DOSs with high comfort (PMV ≅ 0) are selected, and the corresponding energy use for these DOSs is presented in the upper right. In the lower right sub-plot, DOSs with minimal energy expenditure is selected and the corresponding comfort is displayed . The dots are the values of the nominal DOS.

B. Eisenhower, I.M., Energy and Buildings, 2011

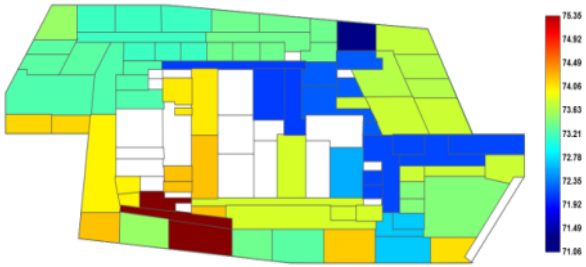
2) Detailed modeling tools.
3) New theory tools.

Big Data Dynamics:
5000 points at 5 minutes intervals!

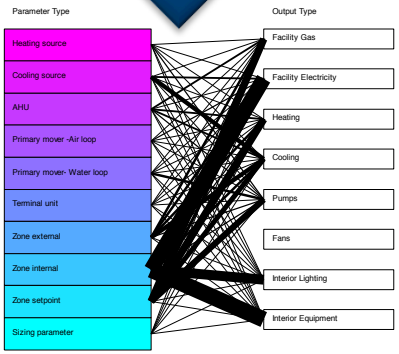
Whole Building Approach

Sensor Inputs

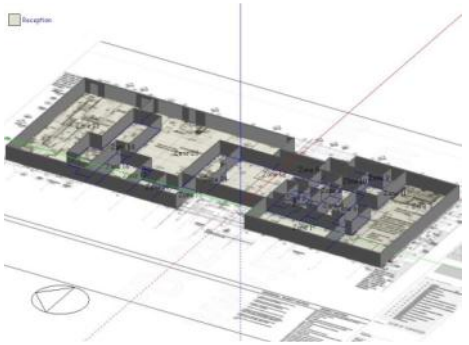
Whole Building Analysis and Control Methods



Energy Visualization and Fault Detection using Koopman Mode Analysis



Sensitivity Analysis and Uncertainty Analysis

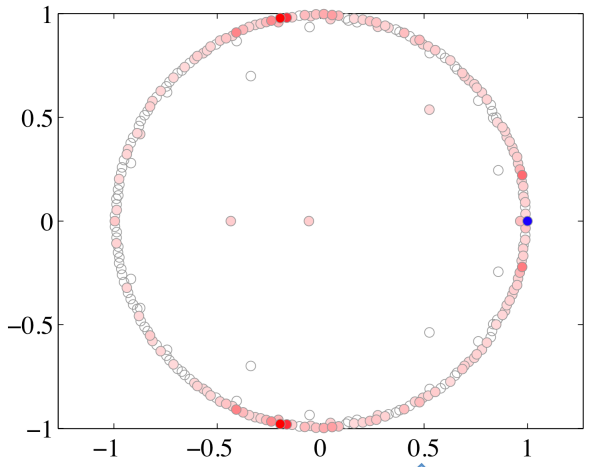


Model Reduction and Validation

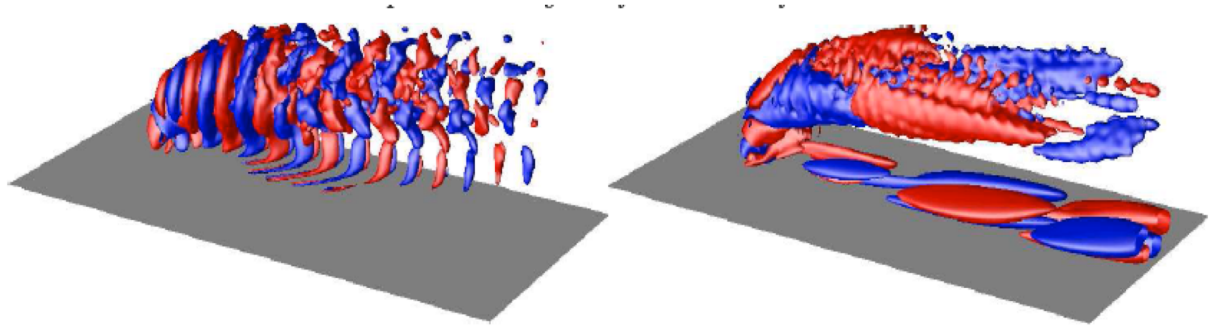
Actionable Recommendations, Supervisory Control

Lower Energy Costs and Improved Comfort

Jet in Cross-Flow



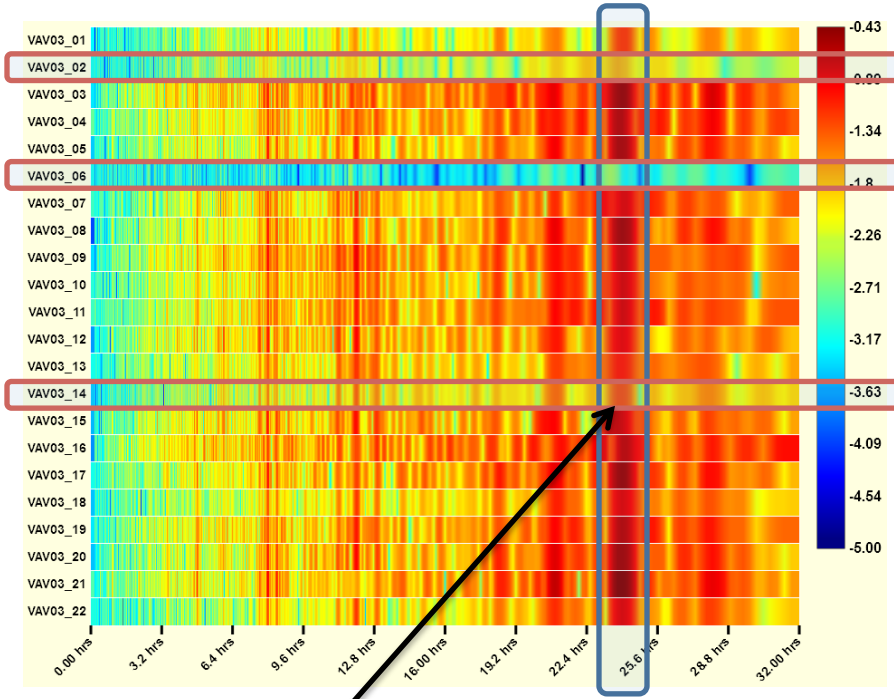
From Rowley et al. Journal of Fluid Mechanics, 2009



Koopman Mode Decomposition (IM, 2005)

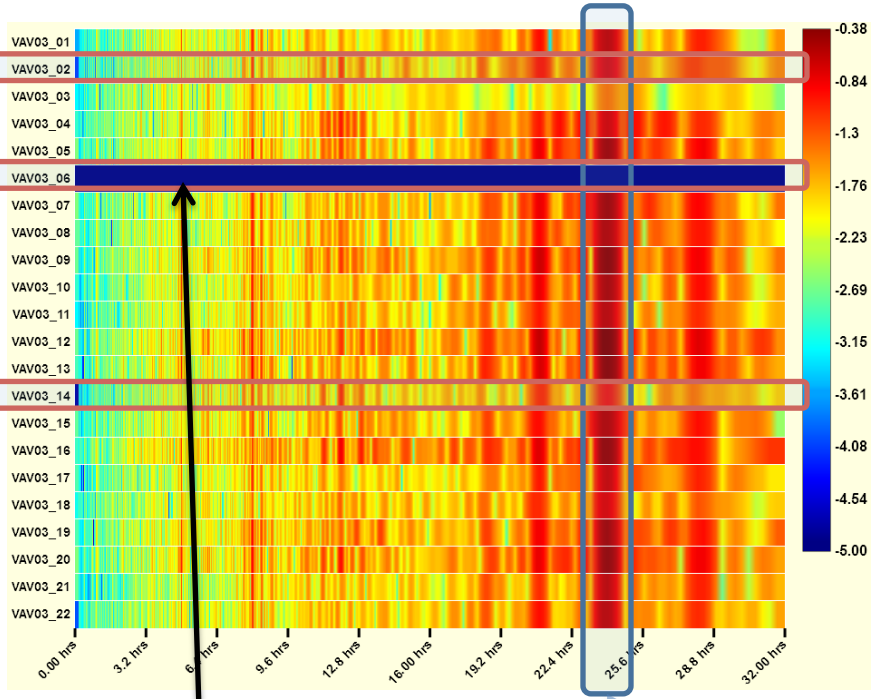
Koopman Spectra and AFDD

VAV Damper Positions



VAV3_02, 03_06, & 3_14 stand out at 24 hr. period

VAV Box Flow



VAV3_06 – Low Spectral Content, Check VAV

24 hour period (Typical)

Heat Dynamics: Koopman Spectra

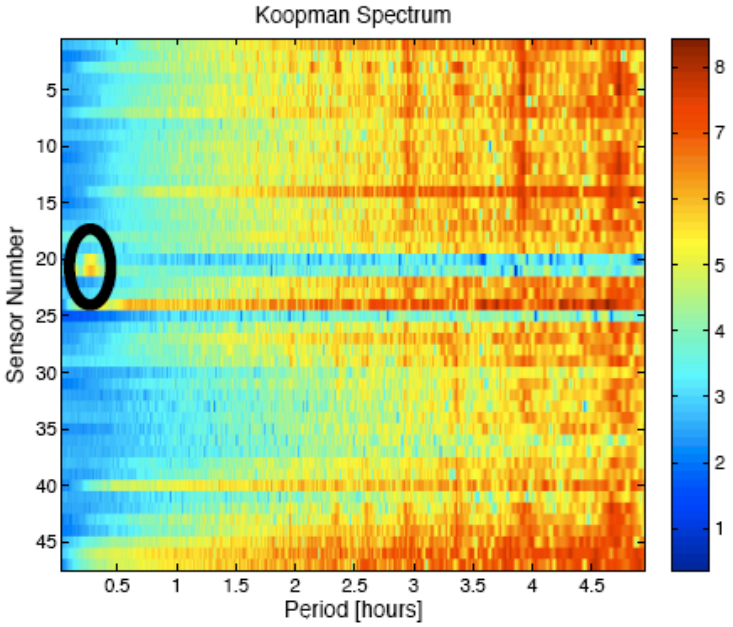


Figure 2: Koopman spectrum for the first floor of Y2E2 sensor data in April 2009. The circled region highlights an area where spectral energy is not expected.

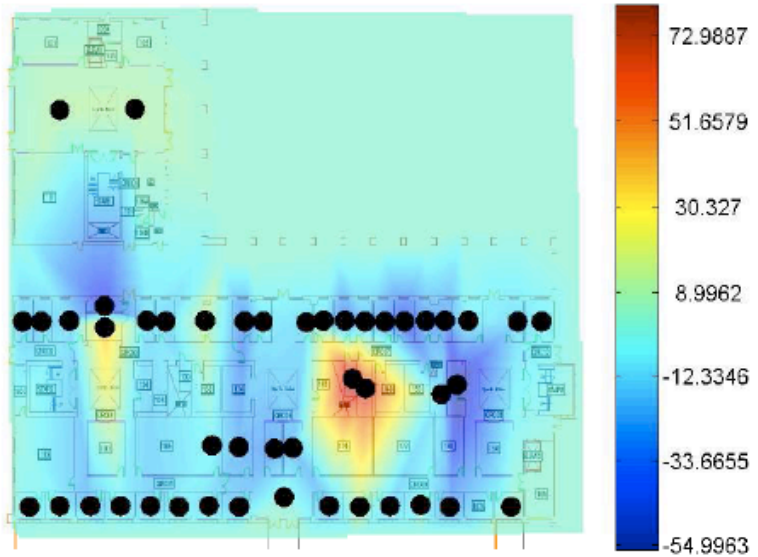
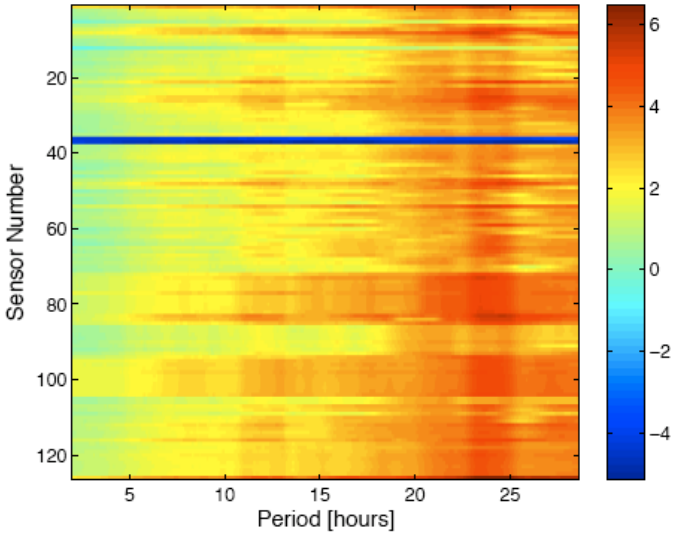
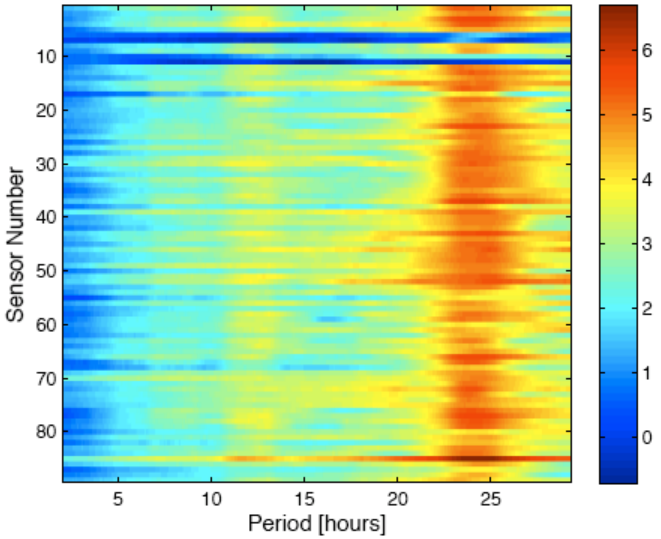


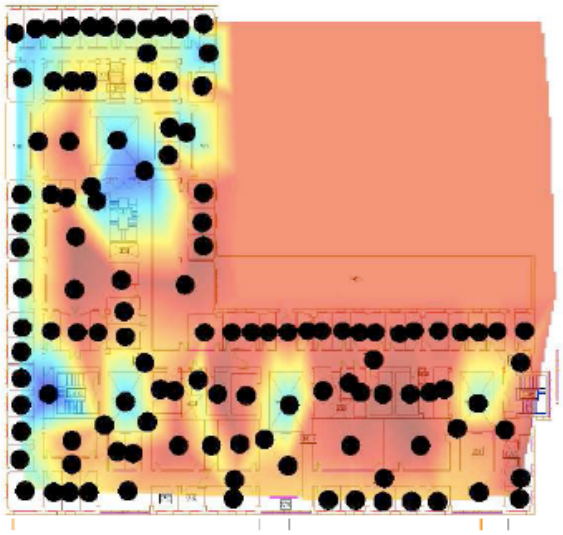
Figure 3: Koopman mode associated with the high frequency spectral energy in Fig. 2

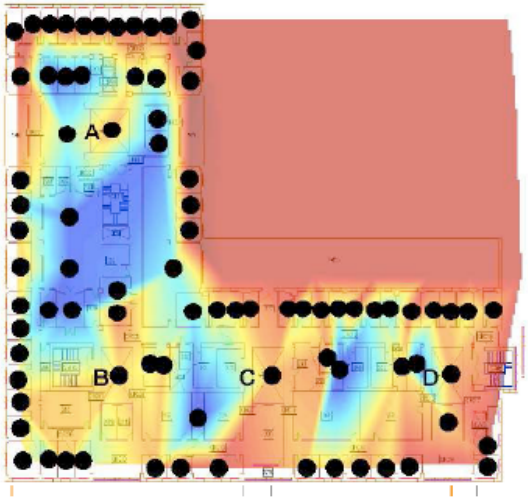
Heat Dynamics: Model Validation

SENSOR DATA









Koopman Modes and Zoning

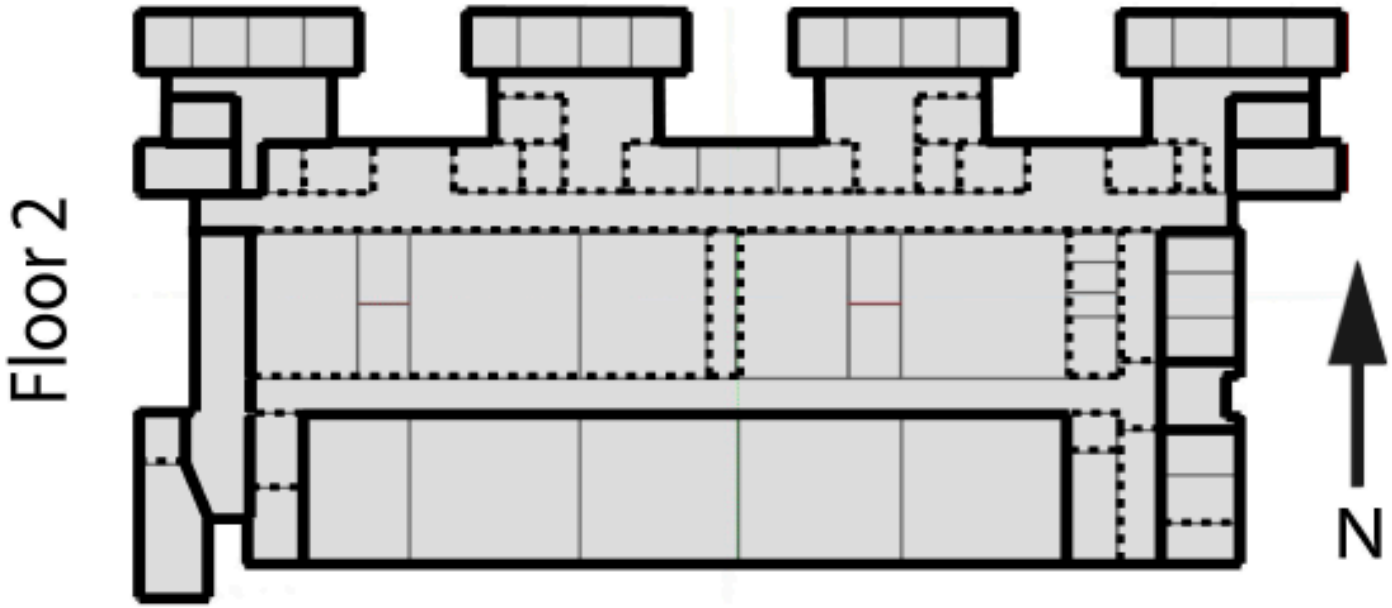


Figure 7: Boundaries of two zoning approximations compared to the original model zone layout (second floor of the building shown). Gray lines indicate zone boundaries of original 191 zone model. Thick solid lines indicate zone boundaries of a 60 zone approximation and dotted lines indicate additional boundaries of a 112 zone approximation.

Spectral Occupancy Detection and Model Error

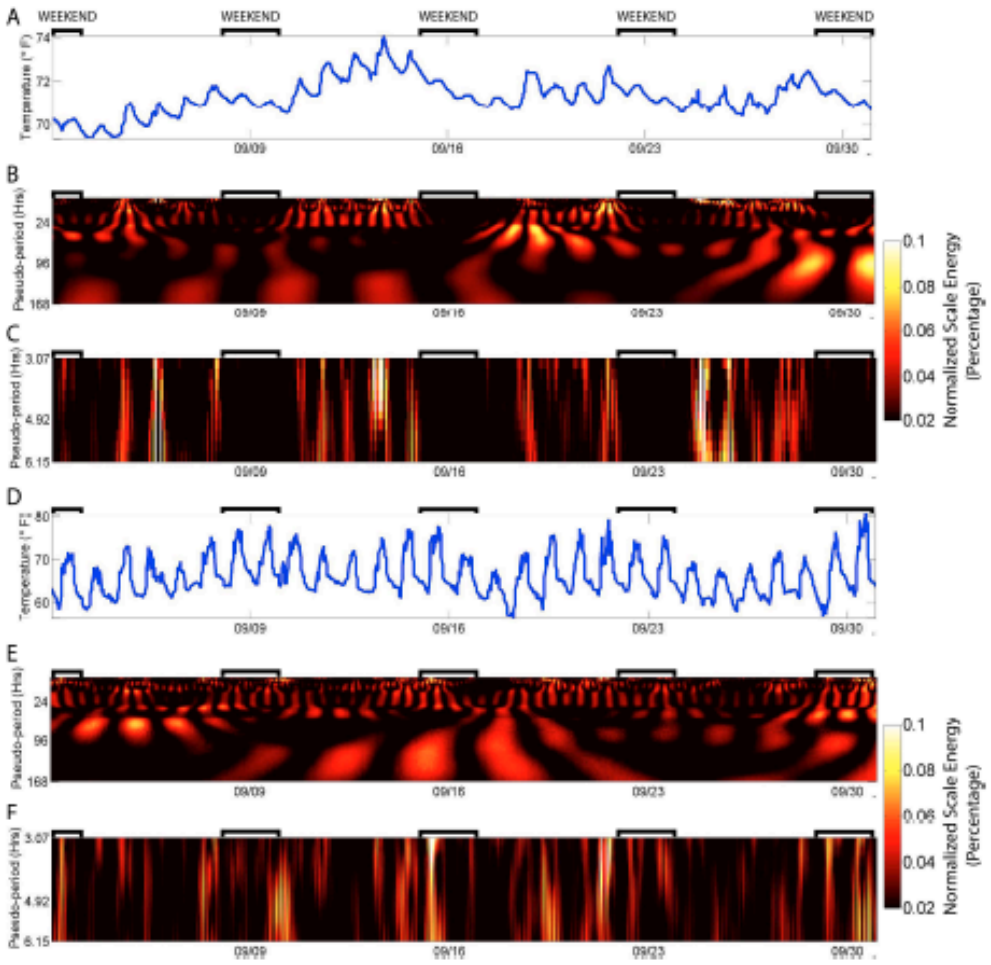


Figure 3: (Color Online) (A) Time-series temperature trend from a naturally ventilated room building sensor. Time-scale representation of room measured temperature data calculated using the continuous wavelet transformation shown over all pseudo-periods (B) and high pseudo-periods (C). (D) Time-series temperature trend of outdoor air temperature. Time-scale representation of outdoor air temperature calculated using the continuous wavelet transformation shown over all pseudo-periods (E) and high pseudo-periods (F).

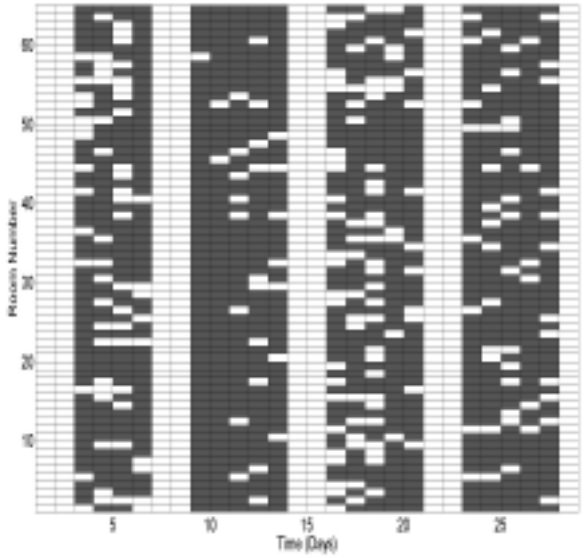


Figure 4: Occupancy status of rooms determined from collected building data over a four week period. Black and white squares signify occupied and unoccupied days respectively.

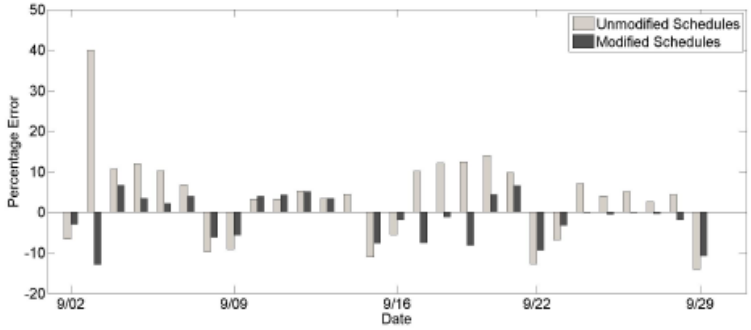
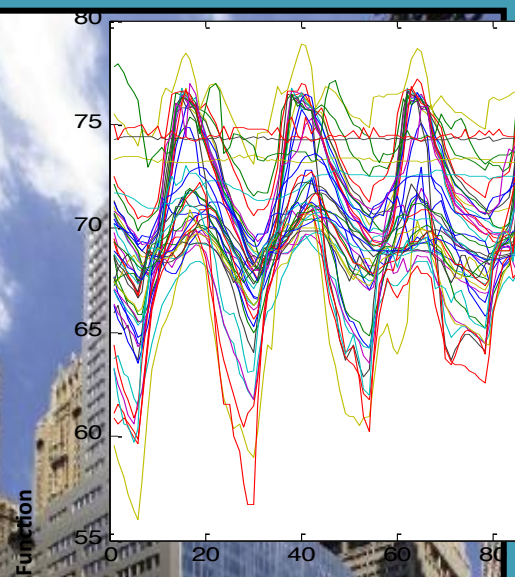
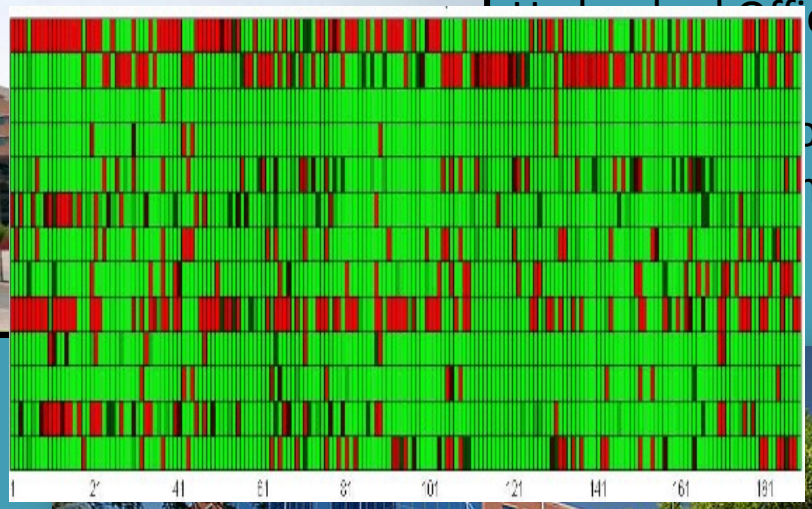


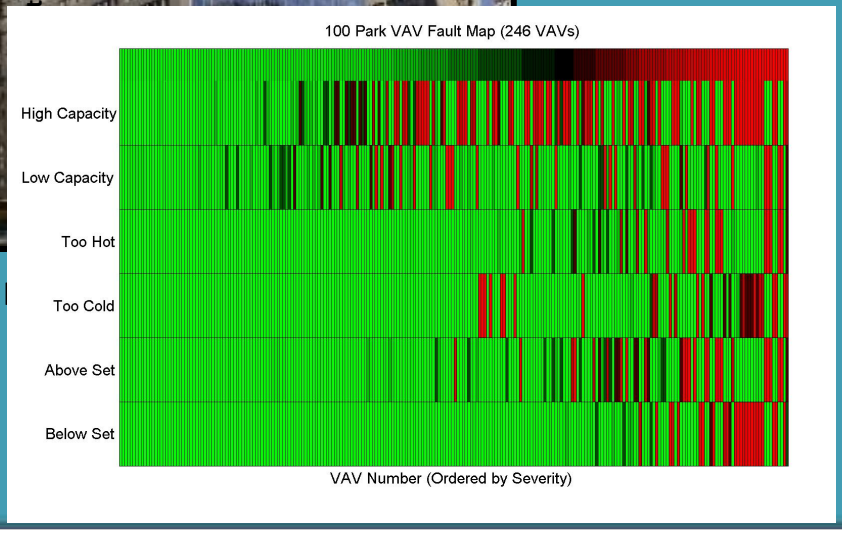
Figure 6: Percentage error of EnergyPlus simulations in predicting building energy usage. The unmodified simulation uses conventional hour-by-hour occupancy schedules created from best estimates of building operation. The modified simulation incorporates predicted fluctuations in occupancy inferred from building temperature data.

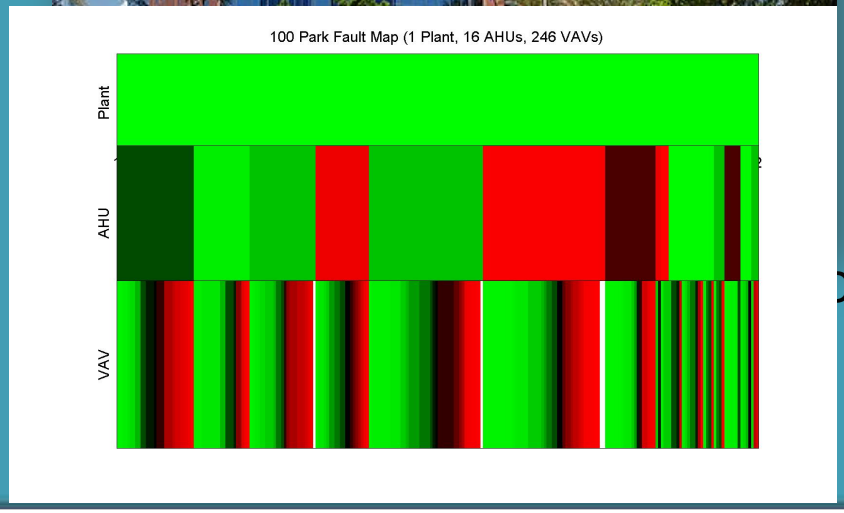
Commercialization: Ecorithm

ECORITHM





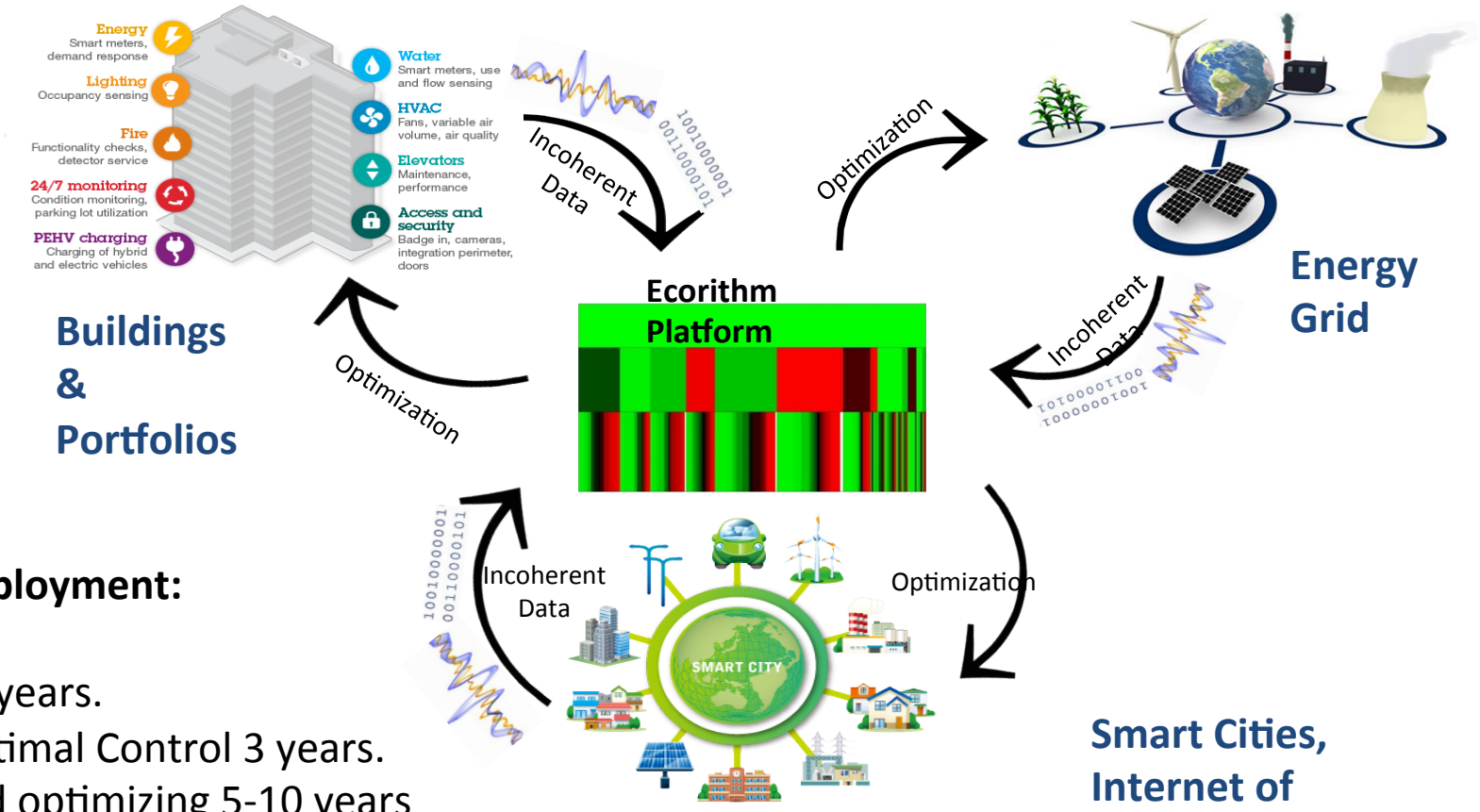




Impact: extended to all buildings above 50K square feet- 40 million US cars of the road.

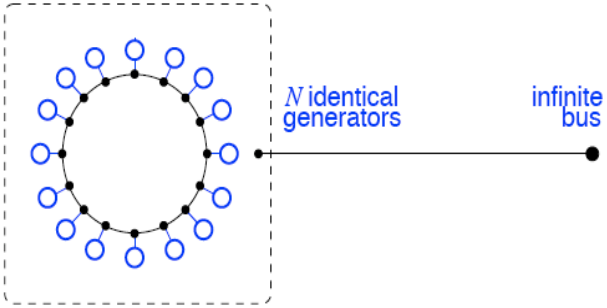
Conclusions and Timeline

- The potential for high ROI with low CAPEX is there, but
- We need to ramp up the data collection base by developing a "poor man's BMS",
- We need to extend methodology that takes into account complex, Big Data Dynamics.
- We need to extend self-healing/optimizing methodology relying on data assimilated models,
- We need data and protocol standardization and normalization methods

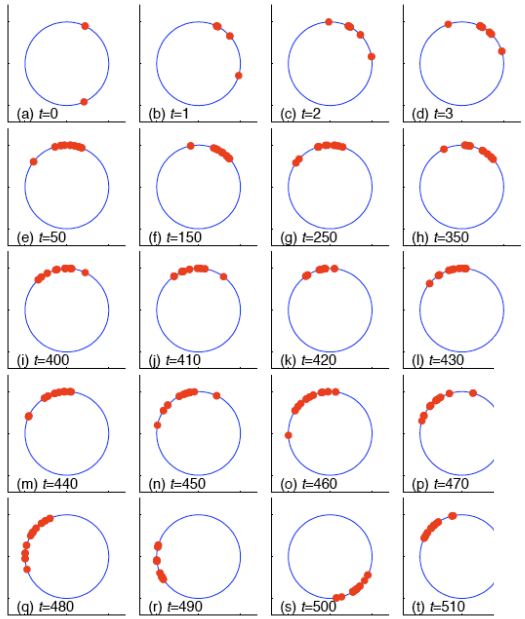


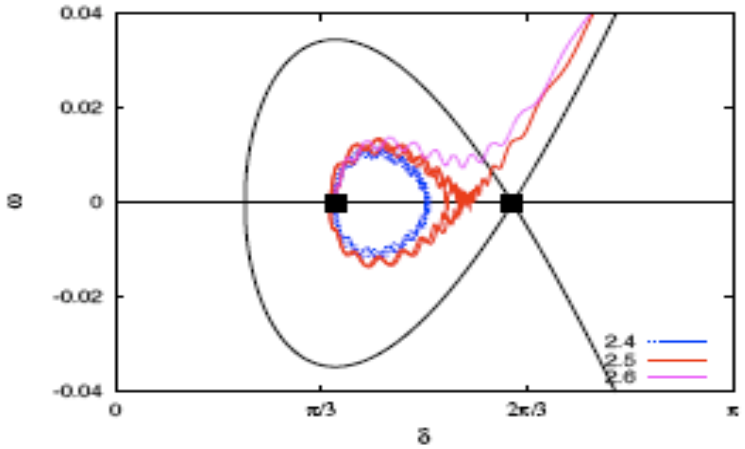
Timeline to commercial deployment:
AFDD 1 year.
Optimization 2 years.
Supervisory Optimal Control 3 years.
Self-healing and optimizing 5-10 years
(with substantial government investment).

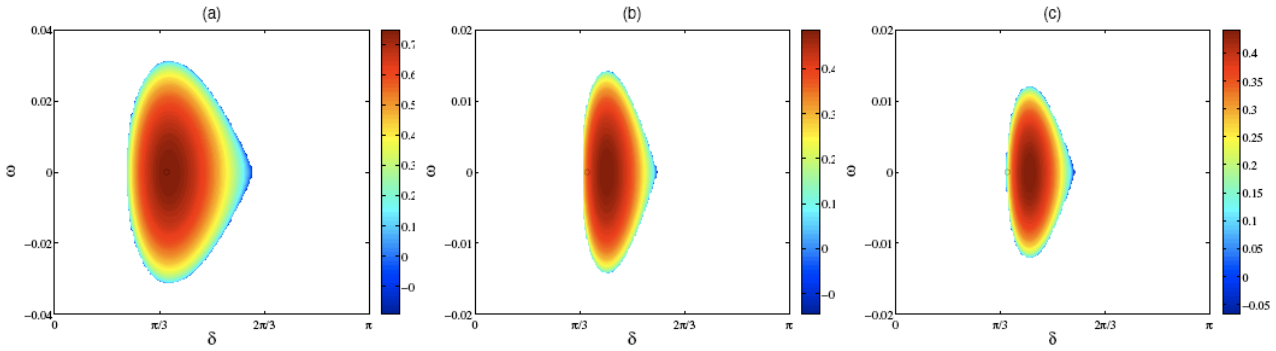
A Power Grid Model



$$\frac{\mathrm{d}\delta_i}{\mathrm{d}t} = \omega_i,$$
$$\frac{\mathrm{d}\omega_i}{\mathrm{d}t} = p_{\mathrm{m}} - b\sin\delta_i + b_{\mathrm{int}}\{\sin(\delta_{i-1} - \delta_i) - \sin(\delta_i - \delta_{i+1})\},$$







Y. Susuki, T. Hikihara (Kyoto)
And I.M. (2009)

Power Grid Stability without Models

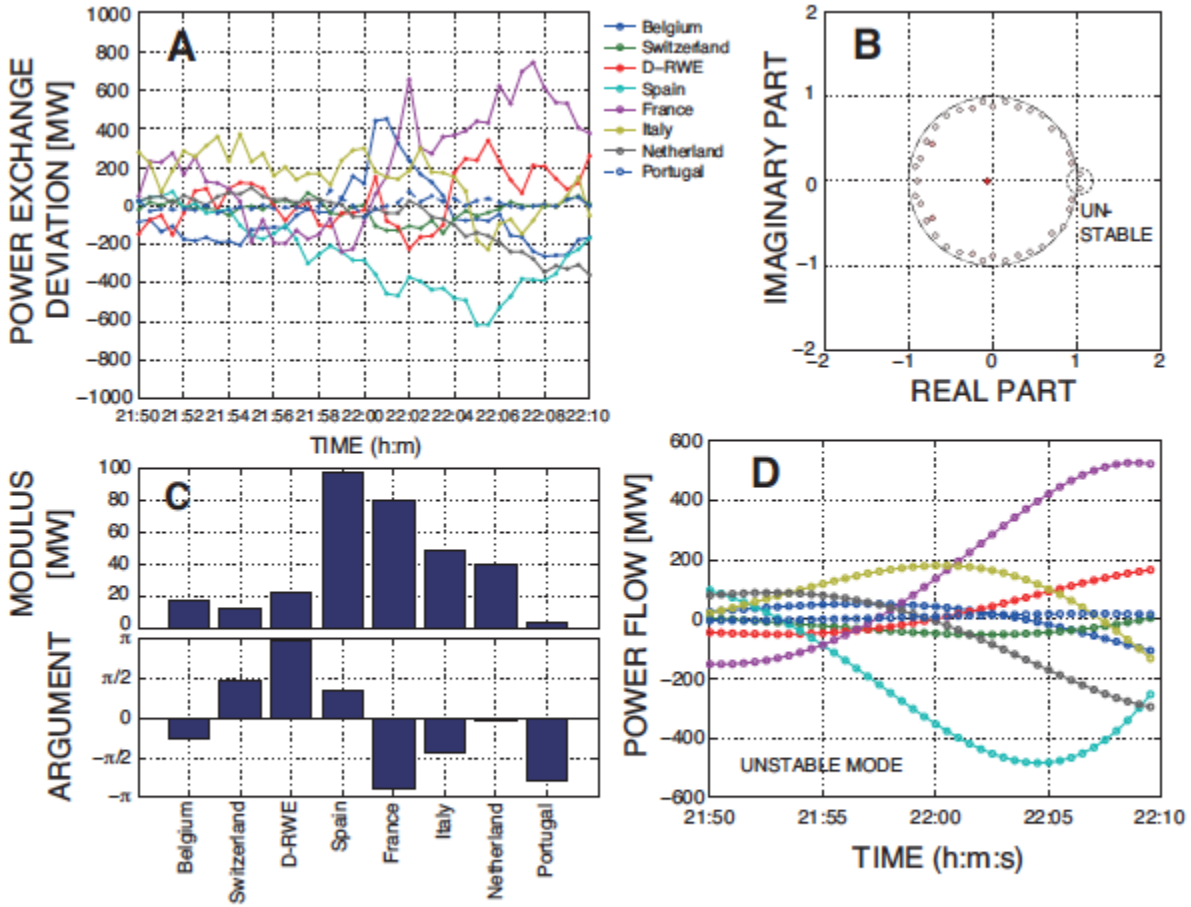
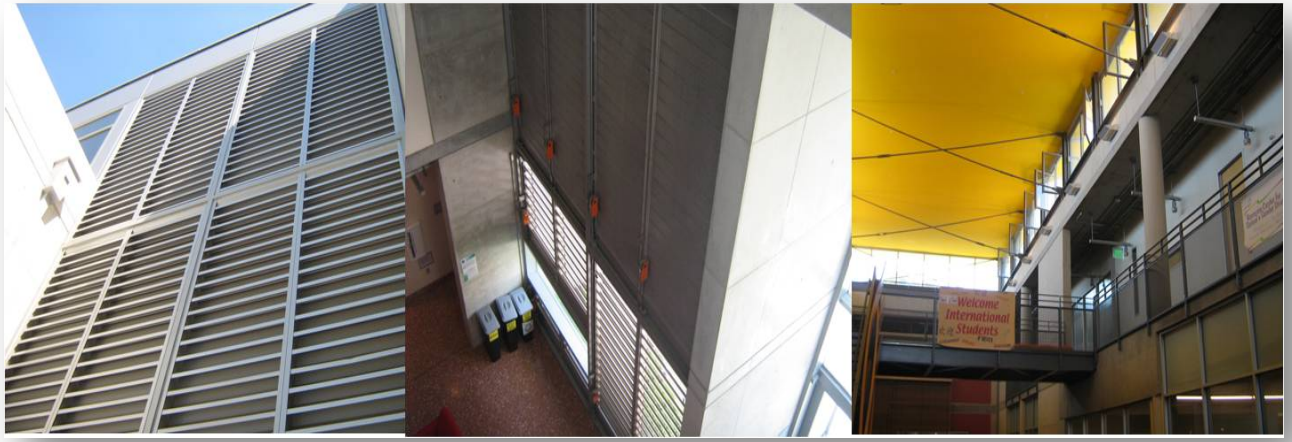


Fig. 2. Koopman mode analysis of power exchange deviations leading to the 2006 system disturbance in the European grid: (A) data on power exchange deviations; (B) Koopman eigenvalues λ_j; (C) modulus and argument vectors of unstable Koopman mode; and (D) dynamics of base flow patterns (9) for the unstable mode. A power exchange deviation is the difference between the actual power exchanges and the scheduled power exchanges with other countries.

With Y. Susuki (Kyoto University), to appear, IEEE TPS (2013)

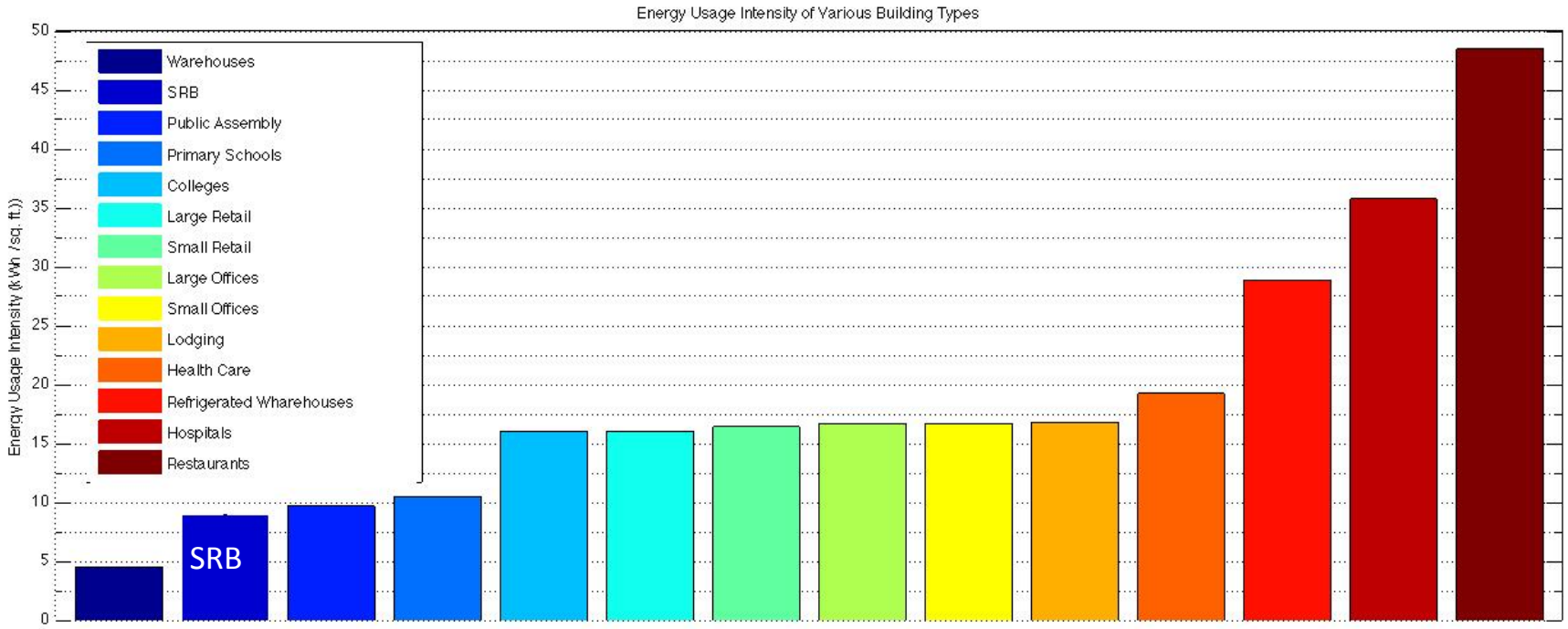
- Student Resources Building
  - 60 kft^2 Design
  - Utilized by students/admin 12-13 hours a day
  - Recent construction (2008) LEED Silver certified
  - Large thermal mass, natural ventilation
  - Some portions are extremely uncomfortable and retrofits are already a must!



Michael Georgescu

Energy Usage Intensity

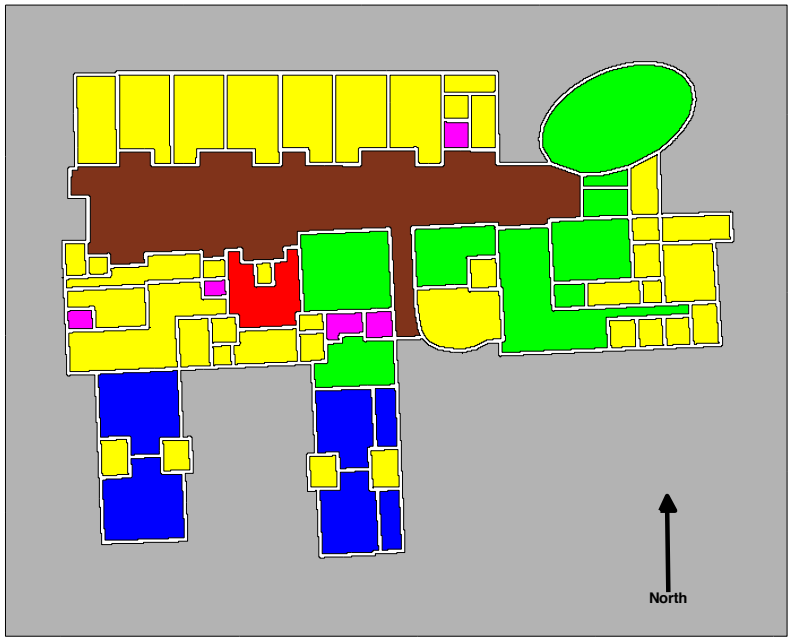
- Energy usage intensity is a performance metric that measures energy usage relative to building area
- It allows buildings of different size to be compared to each other

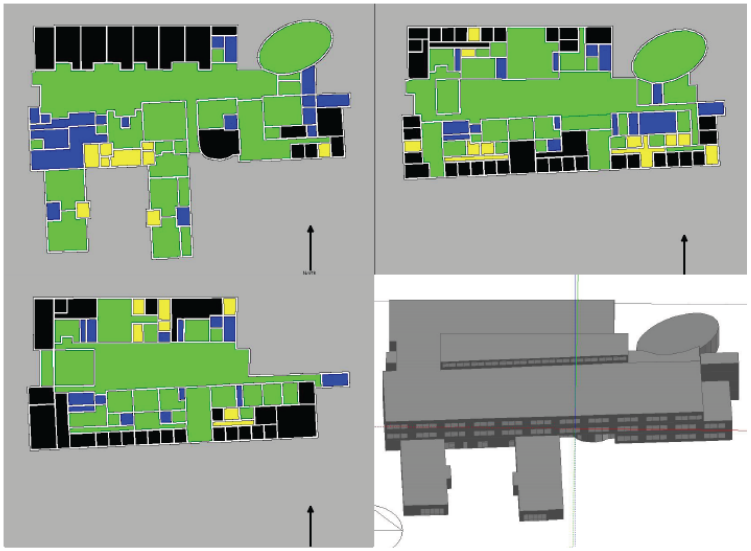


- The SRB uses approximately 600,000 kWH of electricity each year
- For comparison, an average office building of similar size uses 950,000 kWH*

*Based on CBECS average

Tools – Wireless Data

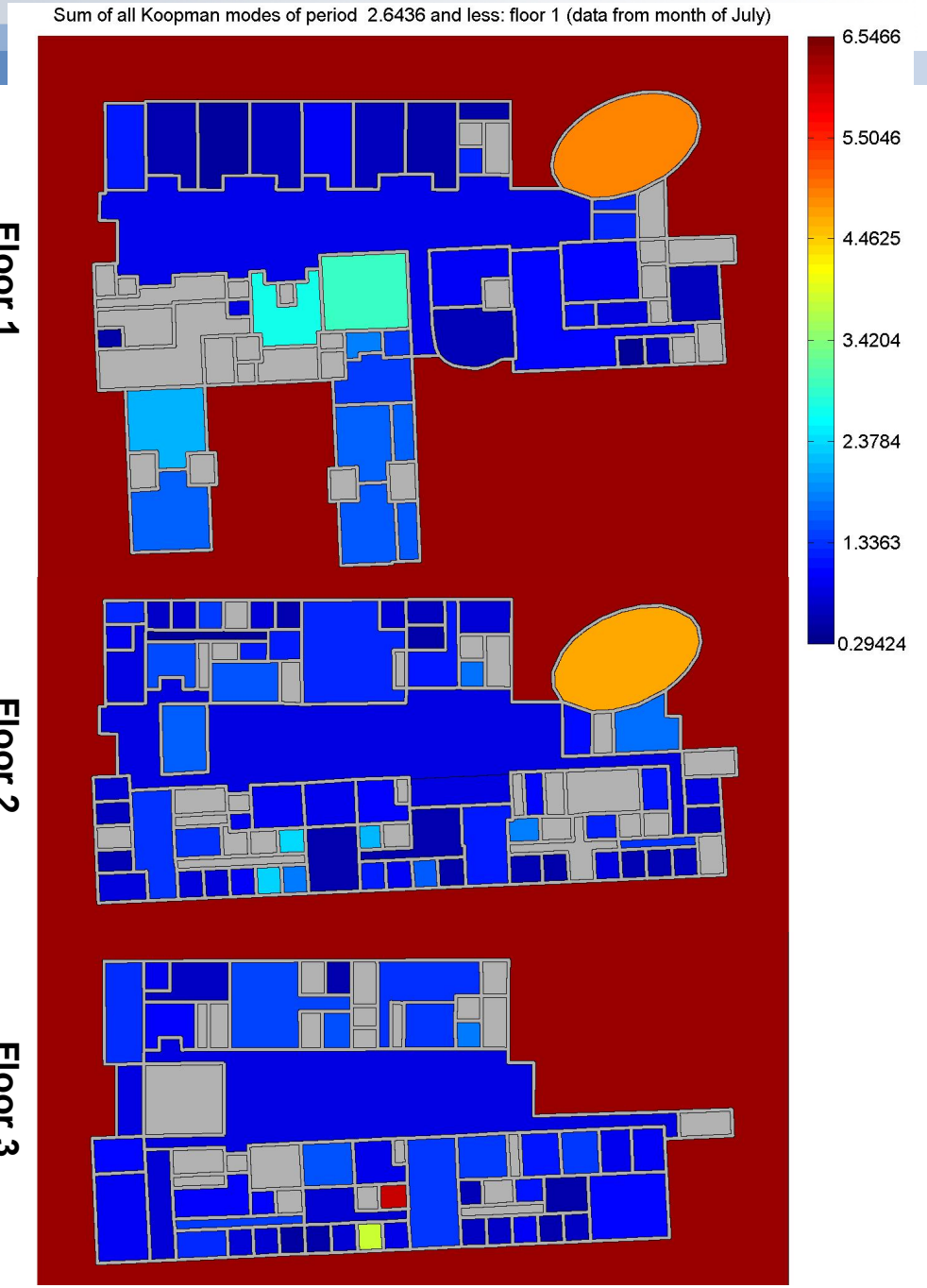




Yellow areas – previously un-sensed
Black areas – wireless sensors added

Unstable auditorium temperature

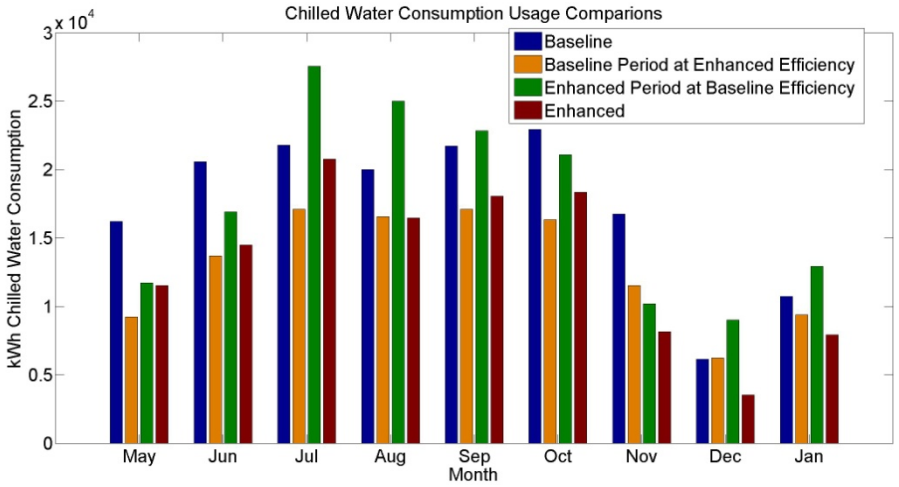
- Spectral energy of auditorium distributed across many higher frequencies
- Summing all high frequency modes (chosen periods <2.6 hrs) shows auditorium has large amount of high frequency spectral energy compared to other rooms served by VAV or CAV units

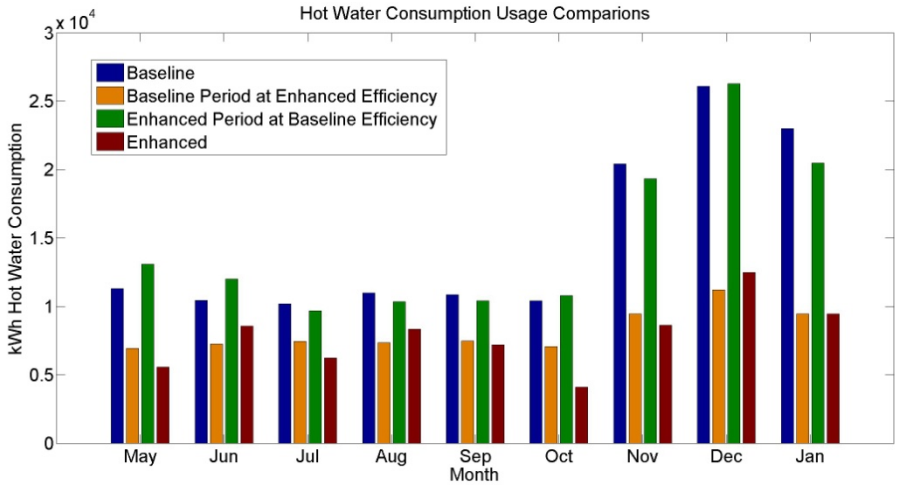


Conclusions and Actions

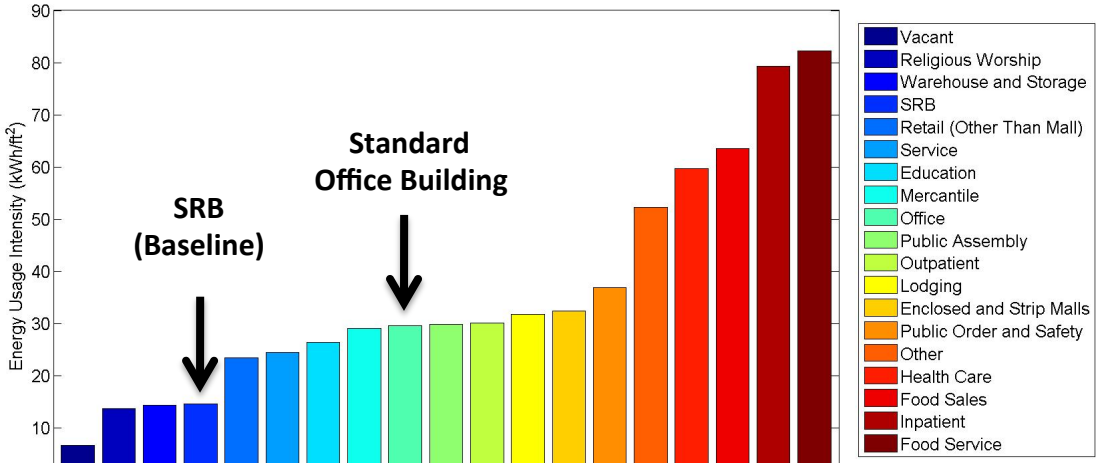
Case Number	Observation	Resulting behavior	Resolution
1 (multi-purpose room)	Unusual heating pattern in adjacent rooms	Excessive heating and cooling	❑Will be addressed during Facilities' reprogramming project of SRB thermostats
2 (DSP center)	Unusual heating pattern in adjacent rooms	Excessive heating and cooling	❑Will be addressed during Facilities' reprogramming project of SRB thermostats
3 (CLAS office)	Unresponsive heating	Excessive heating	❑ Under observation by Facilities
4 (Computer lab)	Inadequate cooling	Uncomfortable temperatures	❑Under observation by Facilities
5 (AHU)	Improper HVAC scheduling	Uncomfortable conditions at night	✓ Schedule adjusted
6 (Boiler)	Excessive boiler operation	Excessive energy use	✓ Schedule adjusted
7 (multi-purpose room)	HVAC prematurely shut down	Uncomfortable conditions	✓ Schedule adjusted

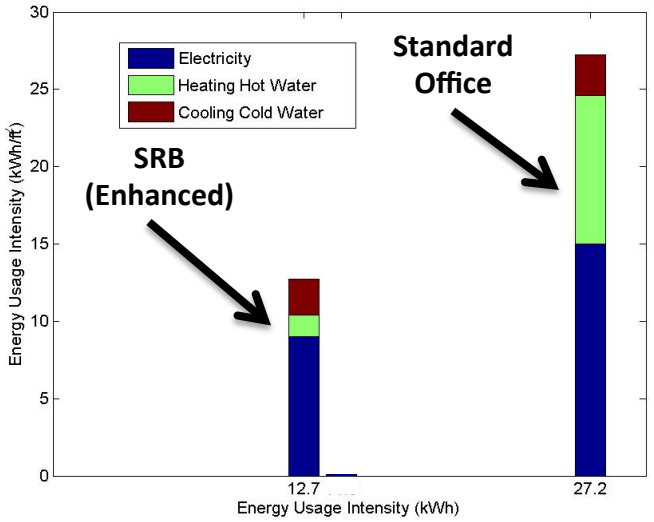
Bottom Line: Energy Usage Intensity





Energy Usage Intensity Comparison





*Standard office building based off of 2003 CBECS building data

Conclusions

- A dynamical systems point of view of building dynamics.
- Nonlinear spectral methods are useful for understanding whole building dynamics.
- Applications for FDD, zoning, model parametrization.
- Approach leads to substantial measured energy savings without loss of comfort.
- Other dynamical systems-based analyses: sensitivity and uncertainty analysis, optimization