*Note, some schematics and images were taken from the internet for this presentation for educational purposes only

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High Performance Buildings:

Measures, Complexity, Current Trends

Bryan Eisenhower

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UCSB

INORGANIC MATERIALS FOR ENERGY CONVERSION AND STORAGE
August 23, 2012

the INSTITUTE for ENERGY EFFICIENCY

CENTER for ENERGY EFFICIENT DESIGN


MONTY PYTHON'S
And Now For Something
COMPLETELY DIFFERENT
DVD
The BEST of Monty Python's Flying Circus

Buildings are everywhere

Buildings are important

Buildings are challenging

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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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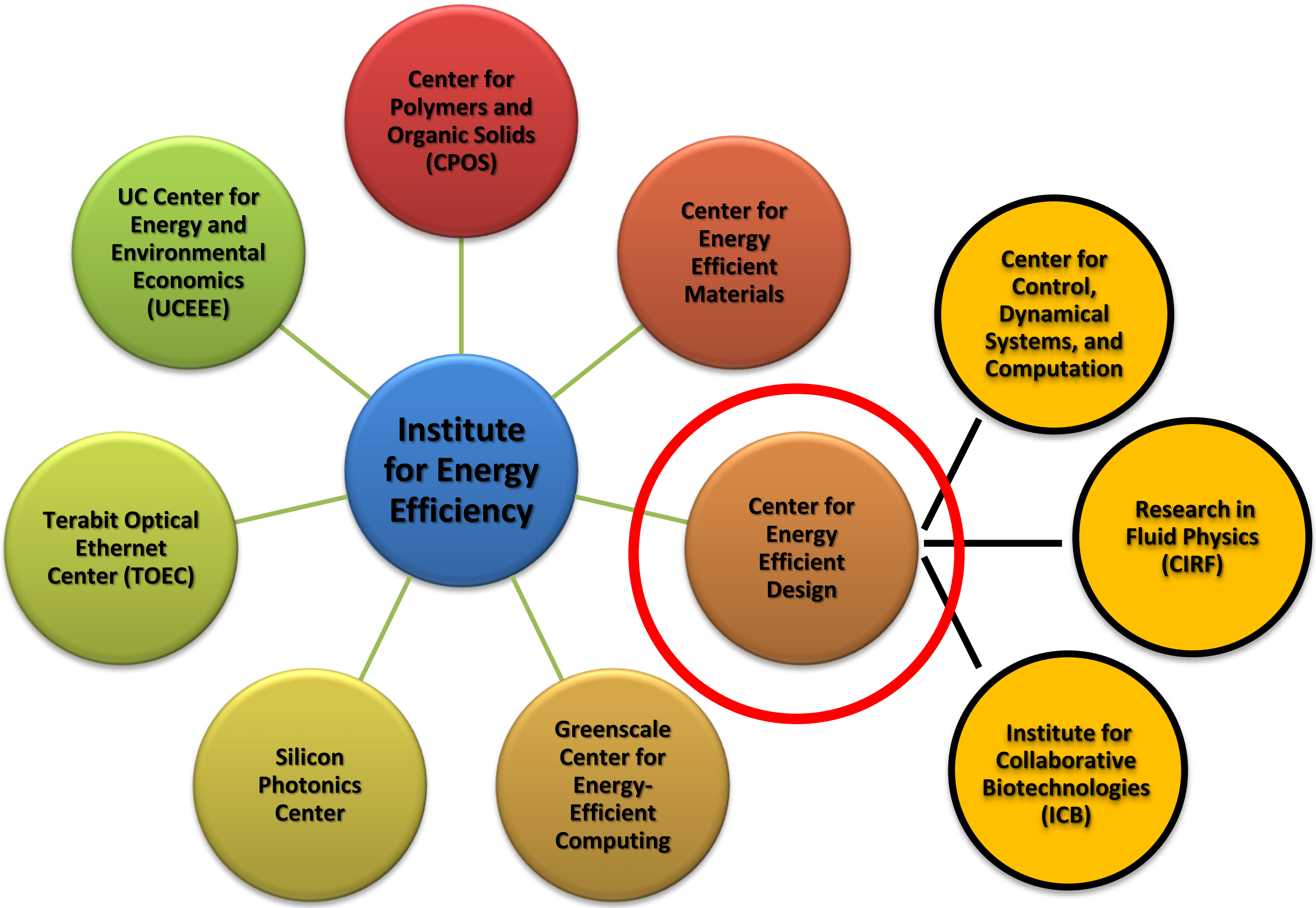

Measuring Performance

Measuring building performance usually combines different metrics into a ratio. Some examples below:

Numerator
Energy consumption / $
Peak Load / $
Energy emissions
% Renewable
Change year / yea
Carbon footprint
Embodied energy
Global warming po
Indoor air quality
….

This balance is dependent upon 'building type'

tor
e foot
(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

Measuring Performance

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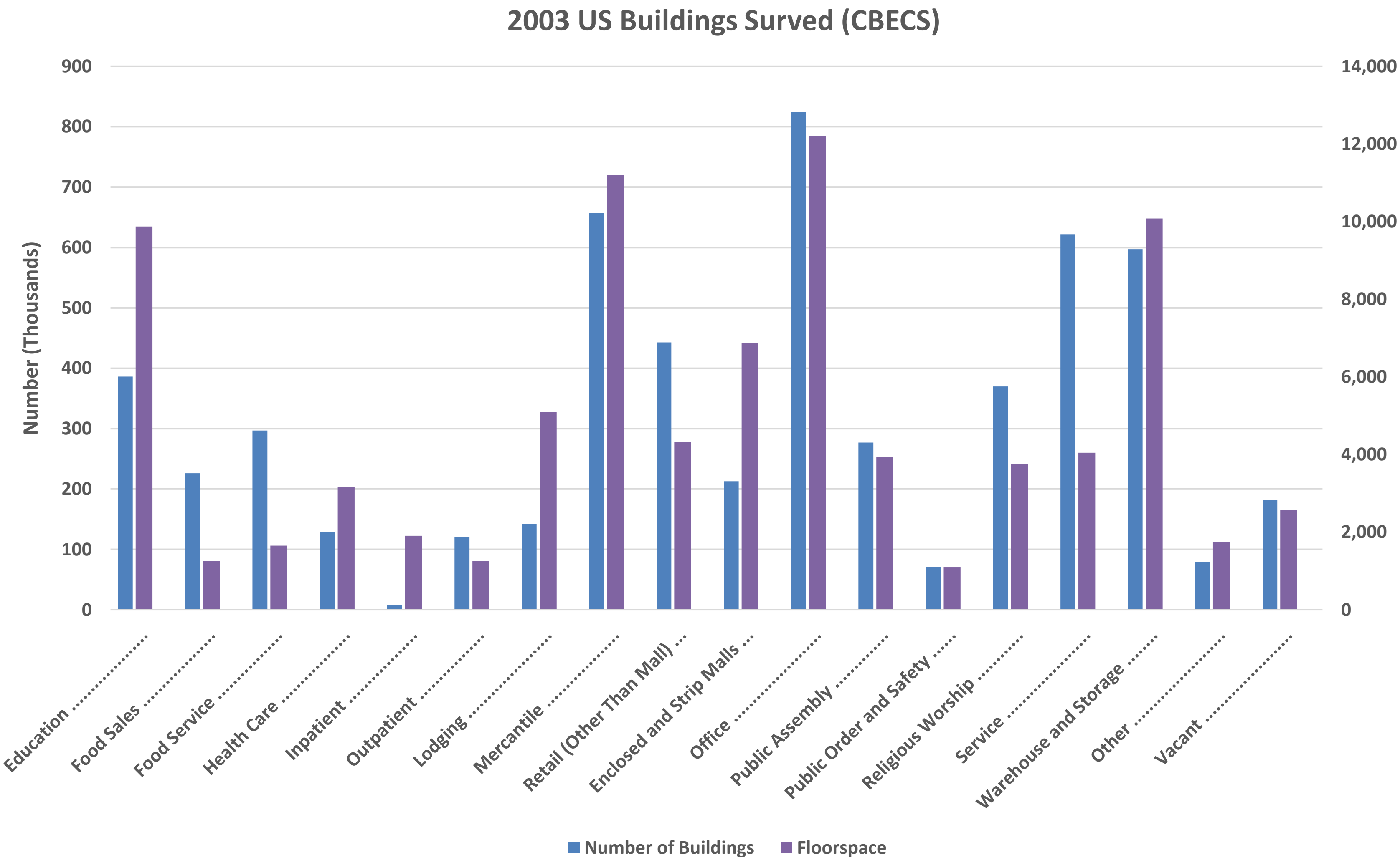
Largest players:

Education, Mercantile, Office, Warehouse



Measuring Performance

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Measuring building performance usually combines different metrics into a ratio. Some examples below:

<u>Numerator</u>

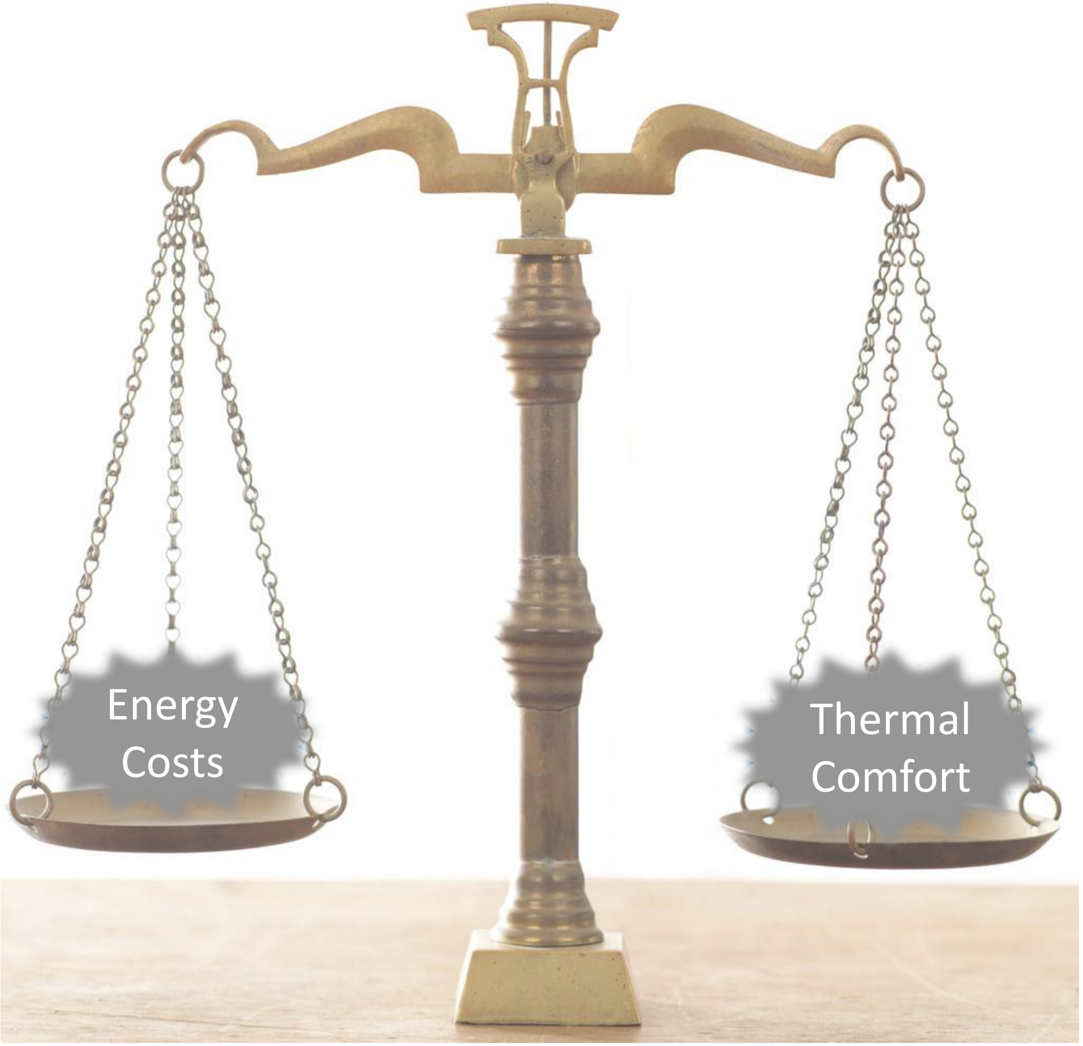
- ➡ Energy consumption / $
- ➡ Peak Load / $
- Energy emissions
- % Renewable
- Change year / year
- Carbon footprint
- Embodied energy
- Global warming potential
- Indoor air quality
- ….

<u>Denominator</u>

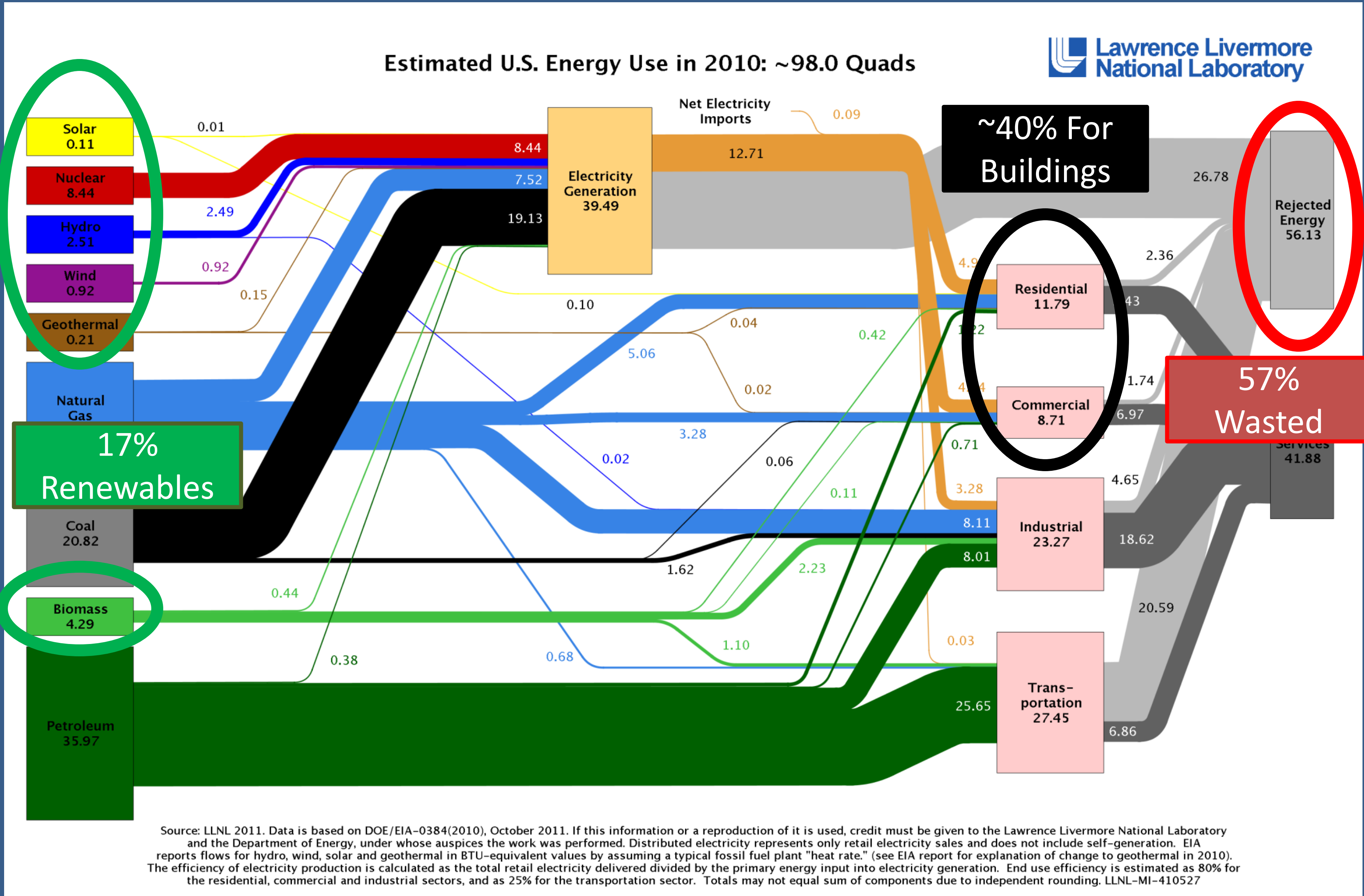
- Per Square foot
- Per visit (e.g. storefront)
- Per transaction
- Per academic degree
- Per lecture hour
- Thermal comfort (measured) ⬅
- Observed comfort (survey)
- Number of service calls
- ….

* The num/den can be flipped

Measuring Performance



Energy Use



Estimated U.S. Energy Use in 2010: ~98.0 Quads
Lawrence Livermore National Laboratory
Solar 0.11
Nuclear 8.44
Hydro 2.51
Wind 0.92
Geothermal 0.21
Natural Gas
17% Renewables
Coal 20.82
Biomass 4.29
Petroleum 35.97
Electricity Generation 39.49
Net Electricity Imports
0.09
12.71
~40% For Buildings
Residential 11.79
Commercial 8.71
Industrial 23.27
Trans-portation 27.45
Rejected Energy 56.13
57% Wasted
Services 41.88
26.78
2.36
1.74
6.97
4.65
18.62
20.59
6.86
0.01
8.44
7.52
19.13
2.49
0.92
0.15
0.10
0.04
0.42
5.06
0.02
3.28
0.02
0.06
0.11
0.71
3.28
8.11
8.01
1.62
2.23
0.44
1.10
0.38
0.68
0.03
25.65
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

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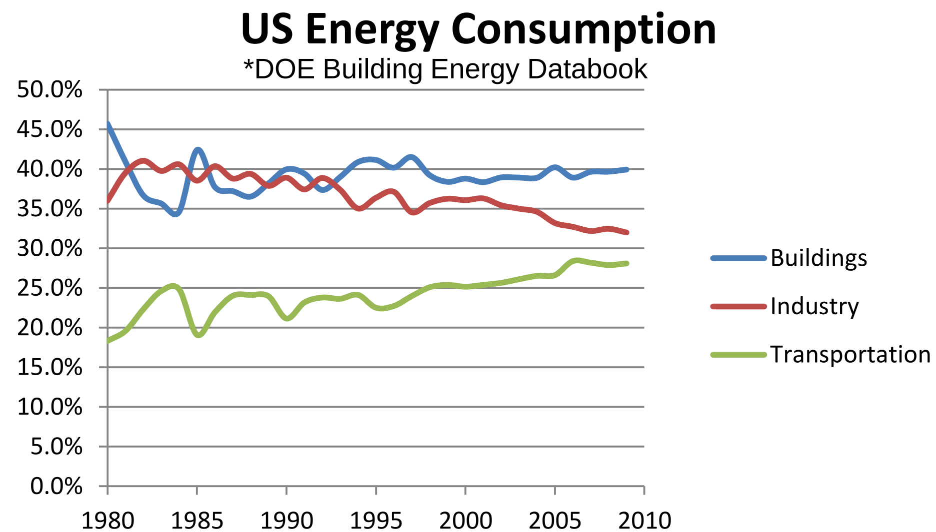
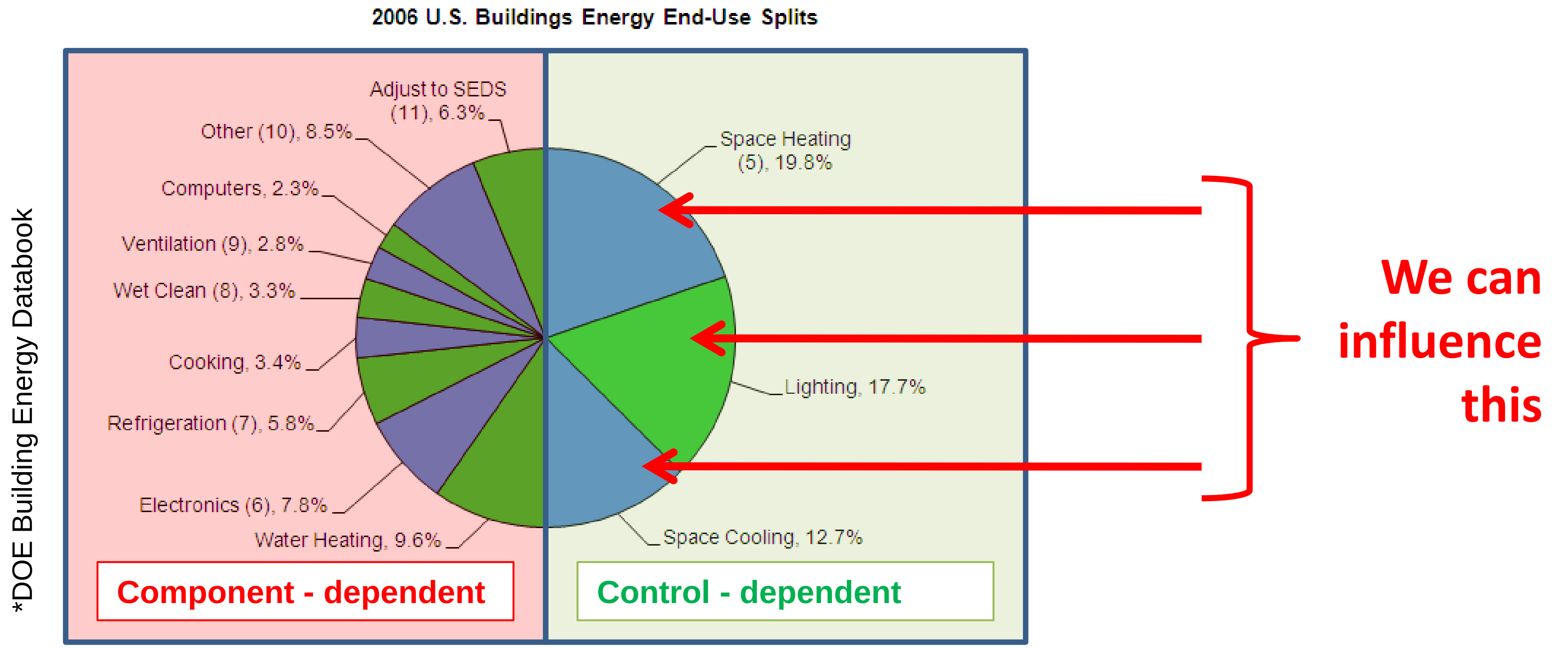
- No drastic changes in time!
- Major portions of energy consumption in buildings is driven by controls

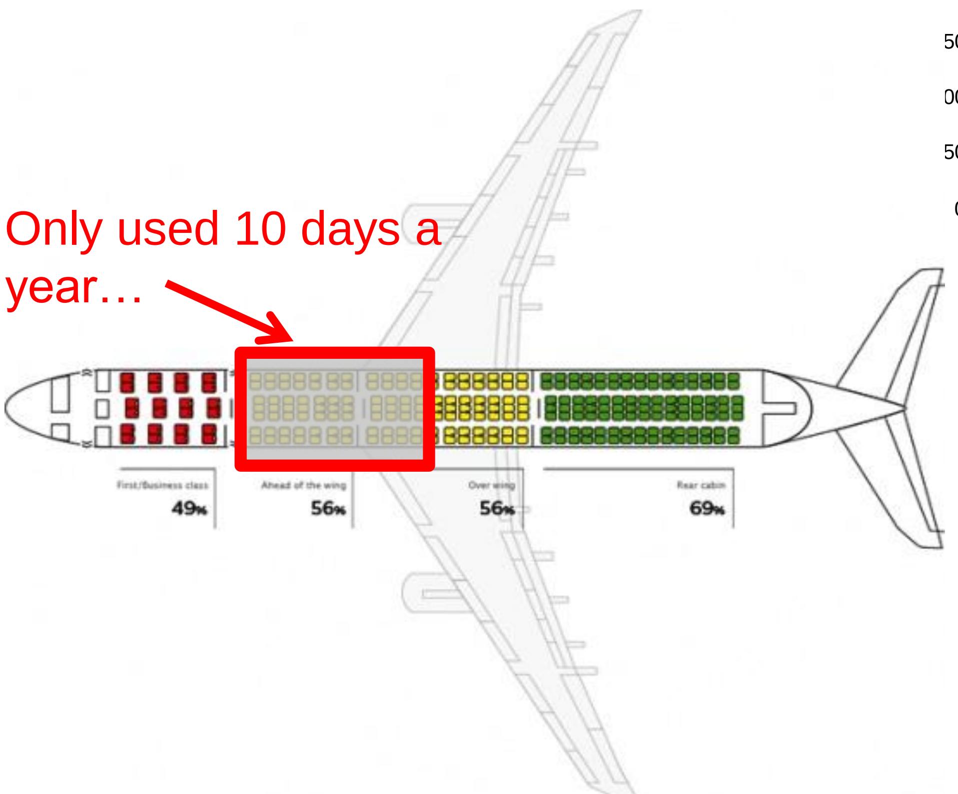


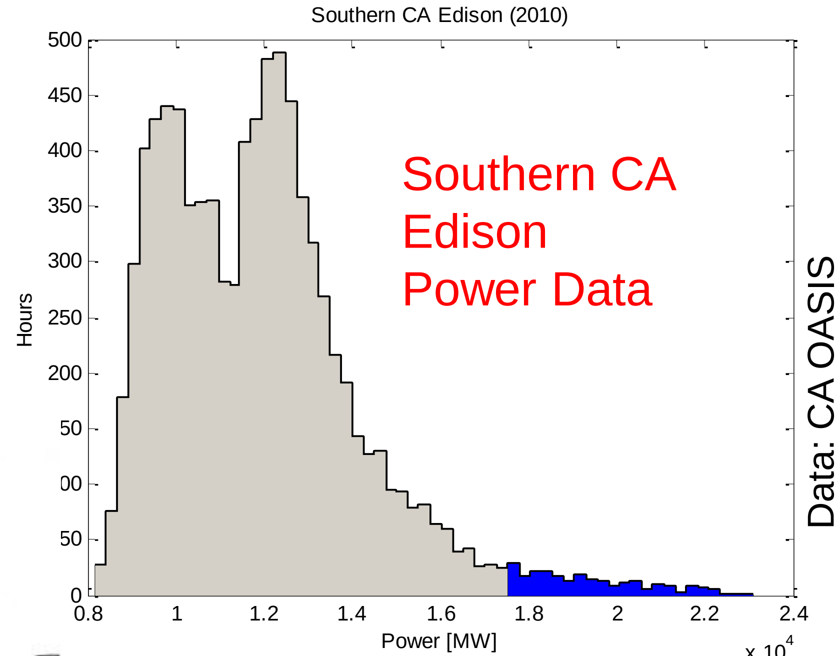


Energy Peak Demand

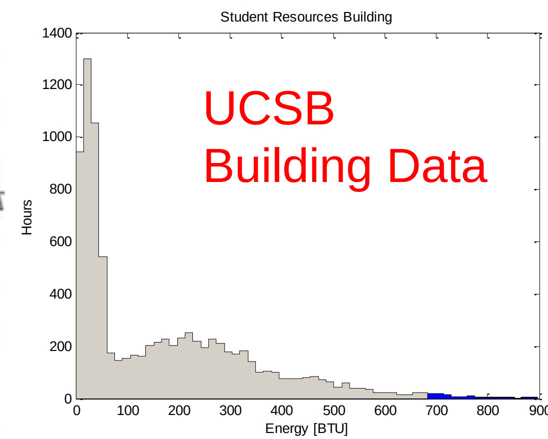
- ❑ Power grid design constraints based on *max* loading, which occurs very *infrequently*

Only used 10 days a year…





Top 25% of power only 2.74% of year.



Top 25% of power only 0.41% of year.

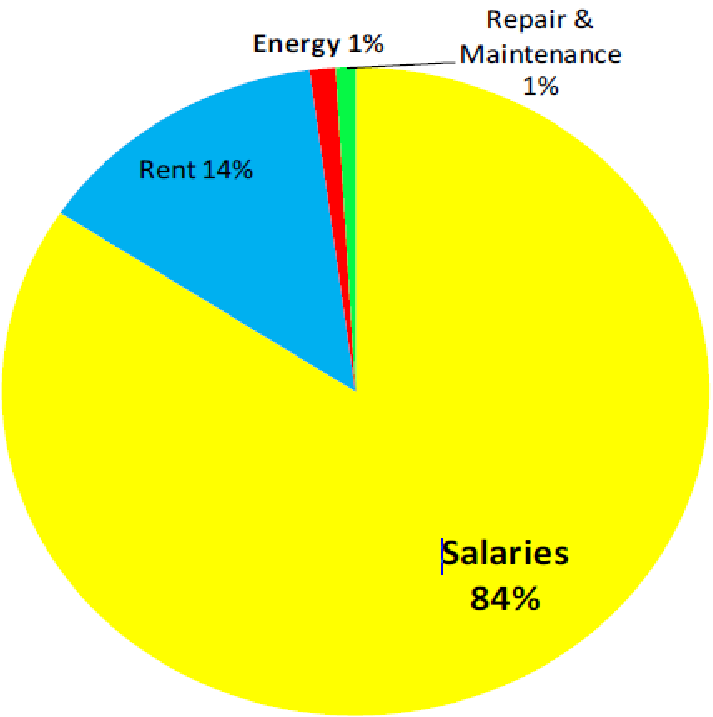
Comfort

- The easy solution to the energy problem is to *'turn the building off'*

Comfort

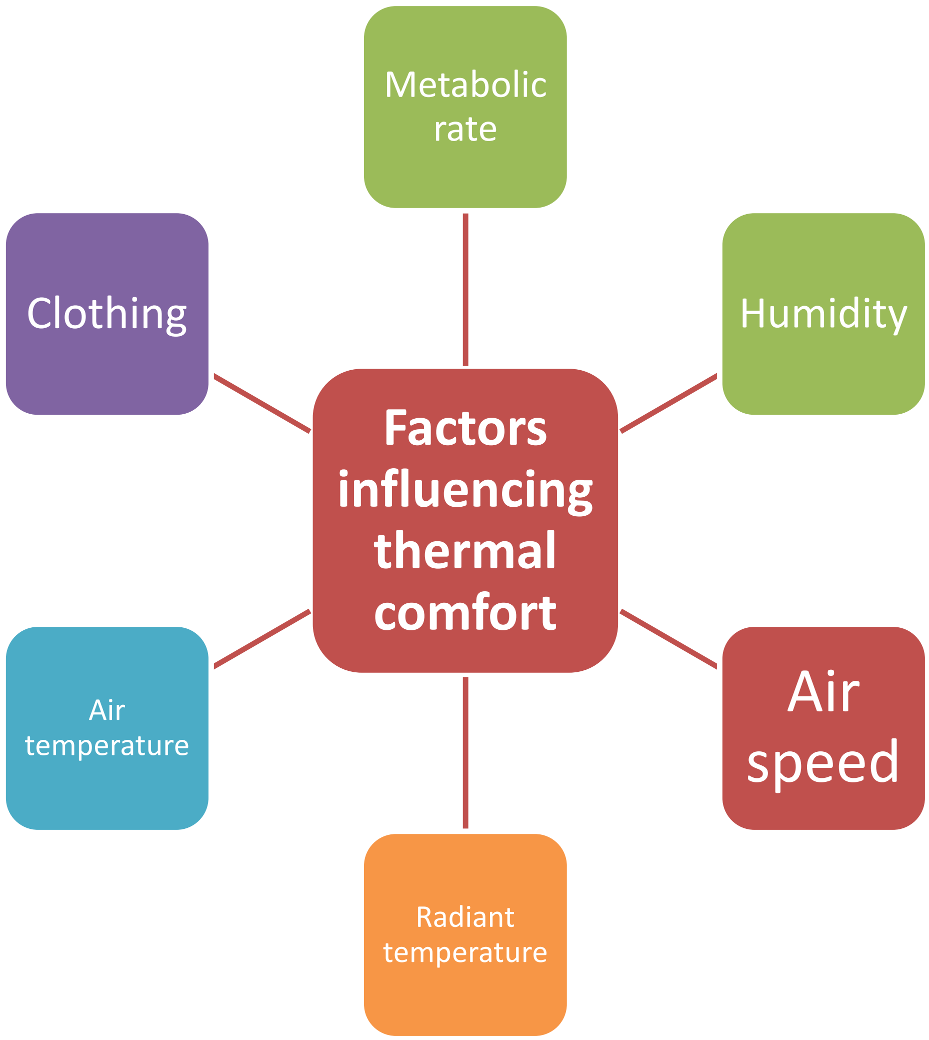
- ➢ The easy solution to the energy problem is to *'turn the building off'*
- ➢ Comfort is needed to:
  - Produce results
  - Earn degrees
  - Sell products
  - Heal people (hospitals)
  - ...

Approximate breakdown of building expenses



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

Thermal Comfort



Source: ASHRAE STD55-2004

Calculating Comfort

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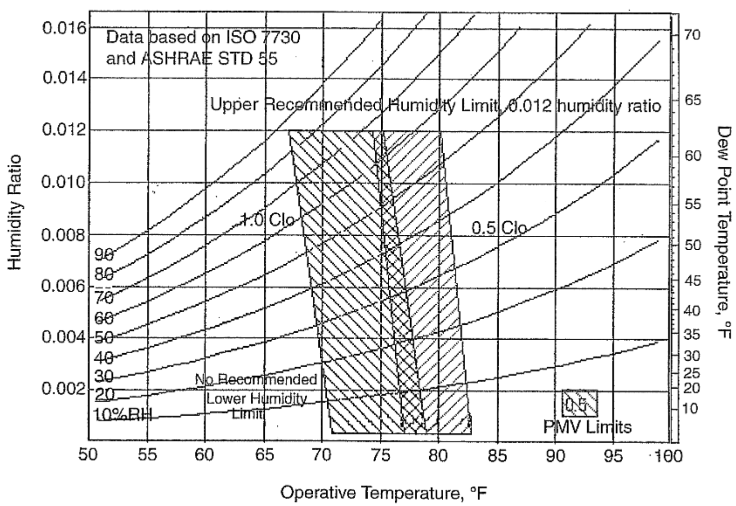
Graph-based

Graphical method with met 1.0-1.3 (office environment)



Source: ASHRAE STD55-2004

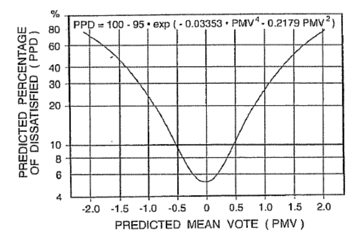
Equation-based

Fanger 1970's:

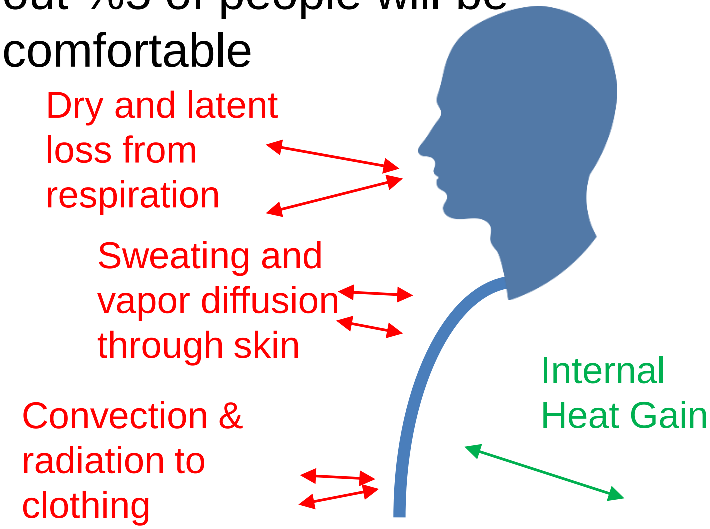
PMV = $(0.303\, e^{-0.036M} + 0.028)L$

M = metabolic rate

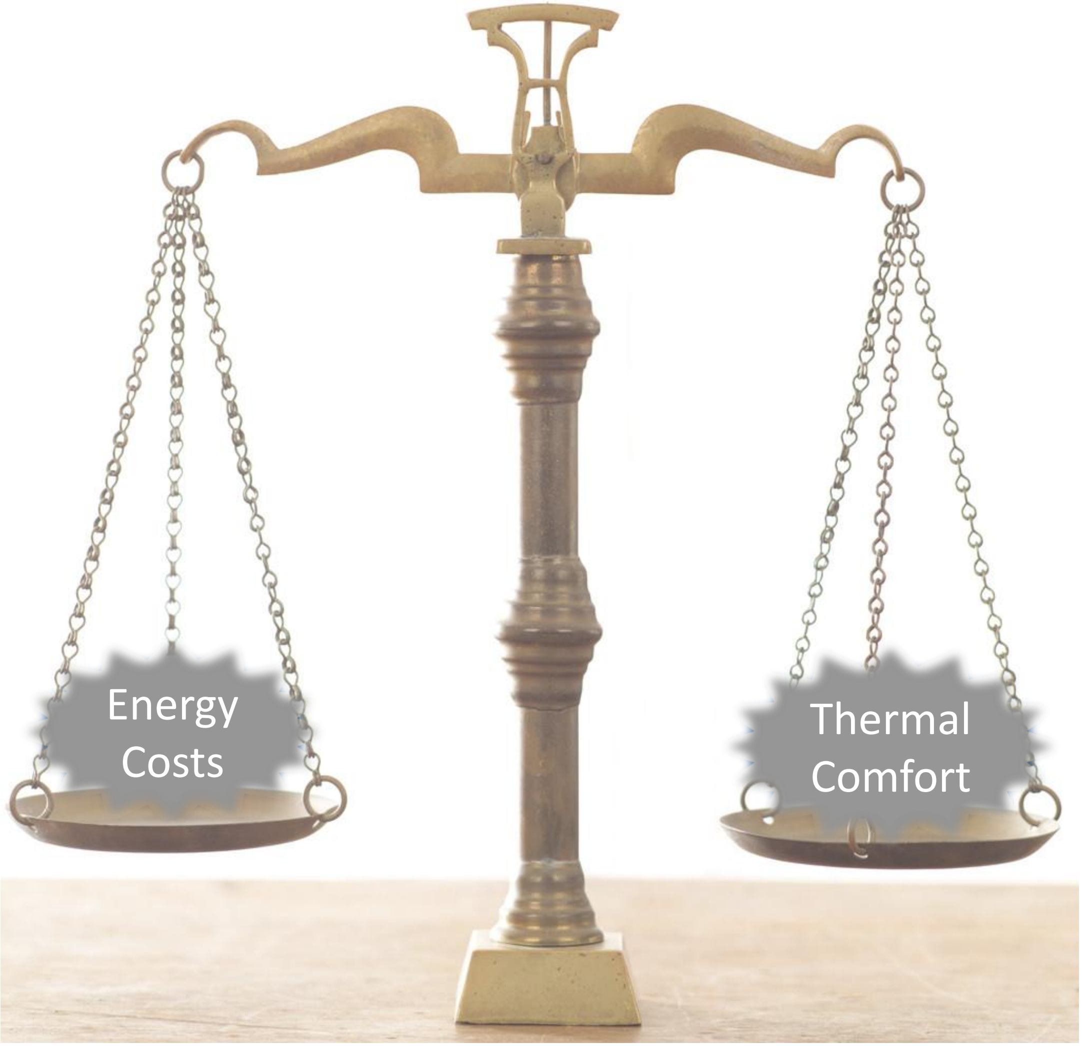
L = Human heat balance



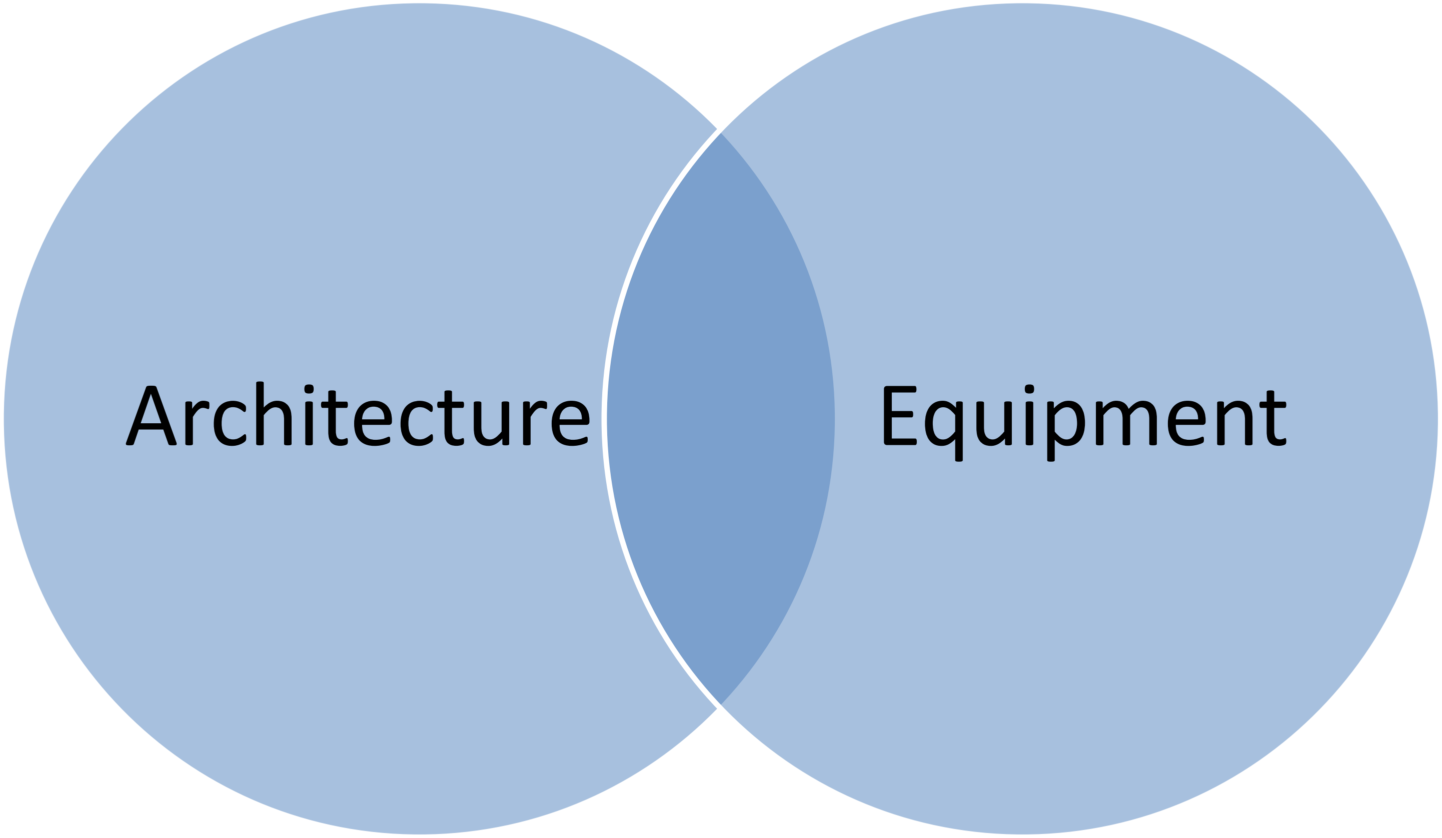
* Note that even with a PMV of 0.0, about %5 of people will be uncomfortable



Measuring Performance



- 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

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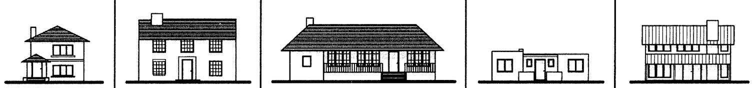
Architectural aspects in building design

Siting

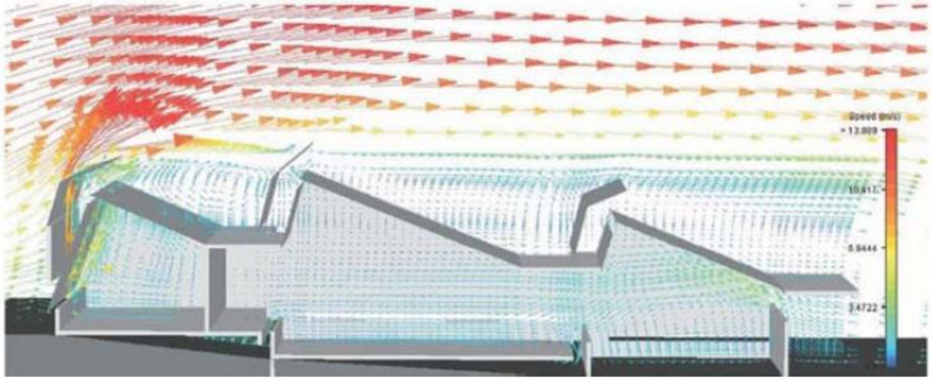
Building site has strong influence on its behavior

- Proximity to other buildings
- Natural shading
- Local air currents (hillside, oceanside, urban)
- Local climates from lakes / water evaporation
- N-S-E-W Orientation

Building orientation can be optimized based on climate and location

Location	Northeast	East	South	Southwest	Northwest
Climate	Cold	Temperate	Hot and humid	Hot and arid	Temperate
Design					
Plan/ envelope ratio	1.3	1.6 to 2.4	1.7 to 3.0	1.3 to 1.6	1.6 to 2.4

Fundamentals of Sustainable Buildings, Friedman



High Performance Buildings, Spring 2011

Near-field flow patterns influence natural convection within a building

Envelope

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- Constructions
- Shading
- Fenestration

Envelope

UC SANTA BARBARA engineering

- ❑ 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)

Envelope

UC SANTA BARBARA engineering

- ❑ Constructions
- ❑ Shading
- ❑ Fenestration

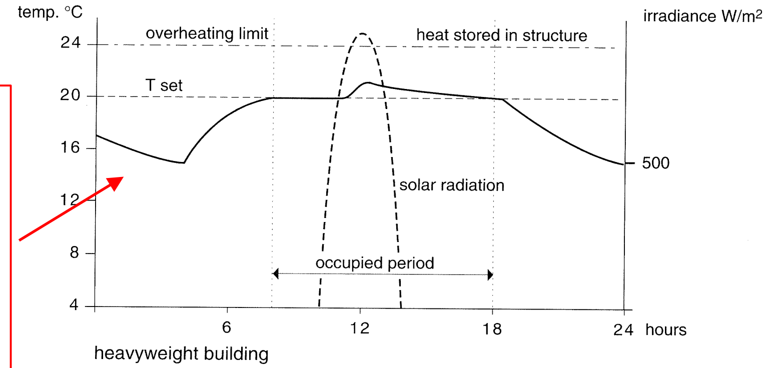
<u>Internal mass</u> has significant influence on *dynamics* of the building

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

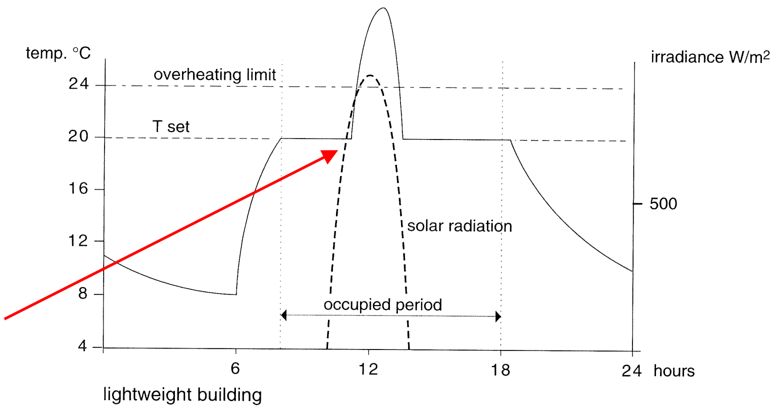
Examples:

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

Slower transients from more mass



Lightweight building responds faster



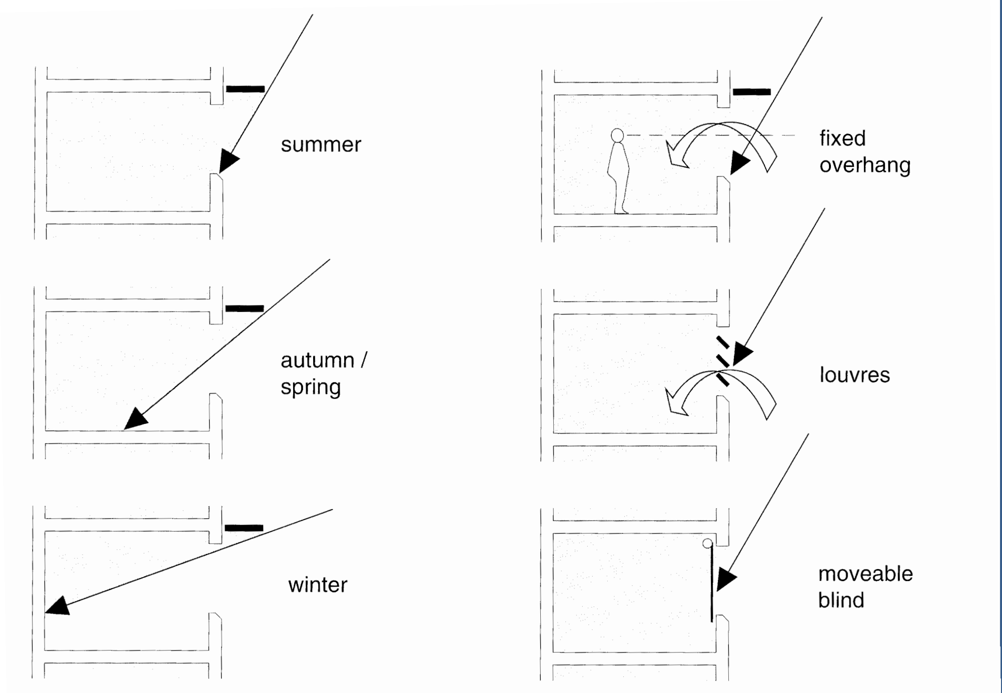
Energy and Environment in Architecture, Baker

Envelope

- ❑ Constructions
- ❑ Shading
- ❑ Fenestration

Shading:

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



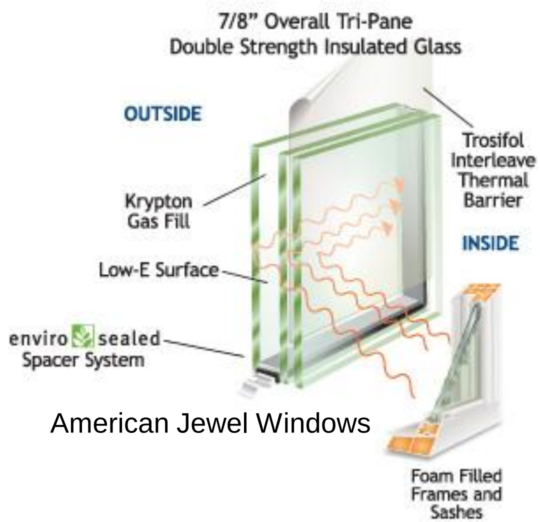
Energy and Environment in Architecture, Baker

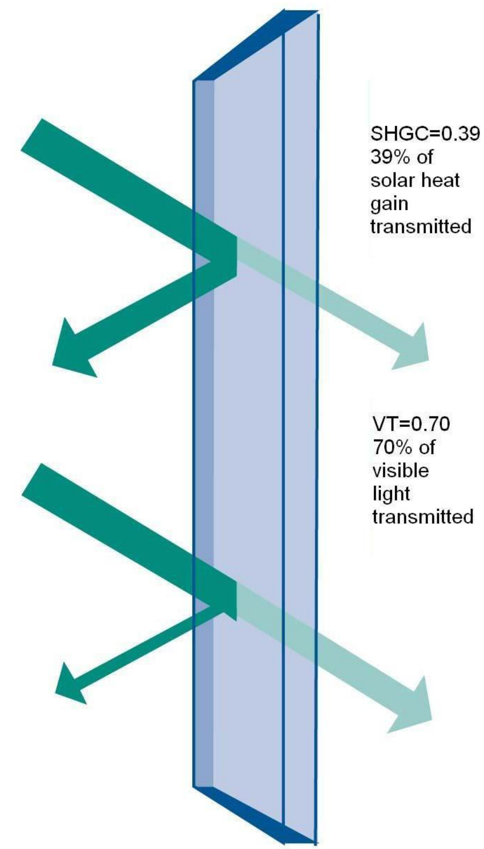
Envelope

- ❑ Constructions
- ❑ Shading
- ❑ Fenestration

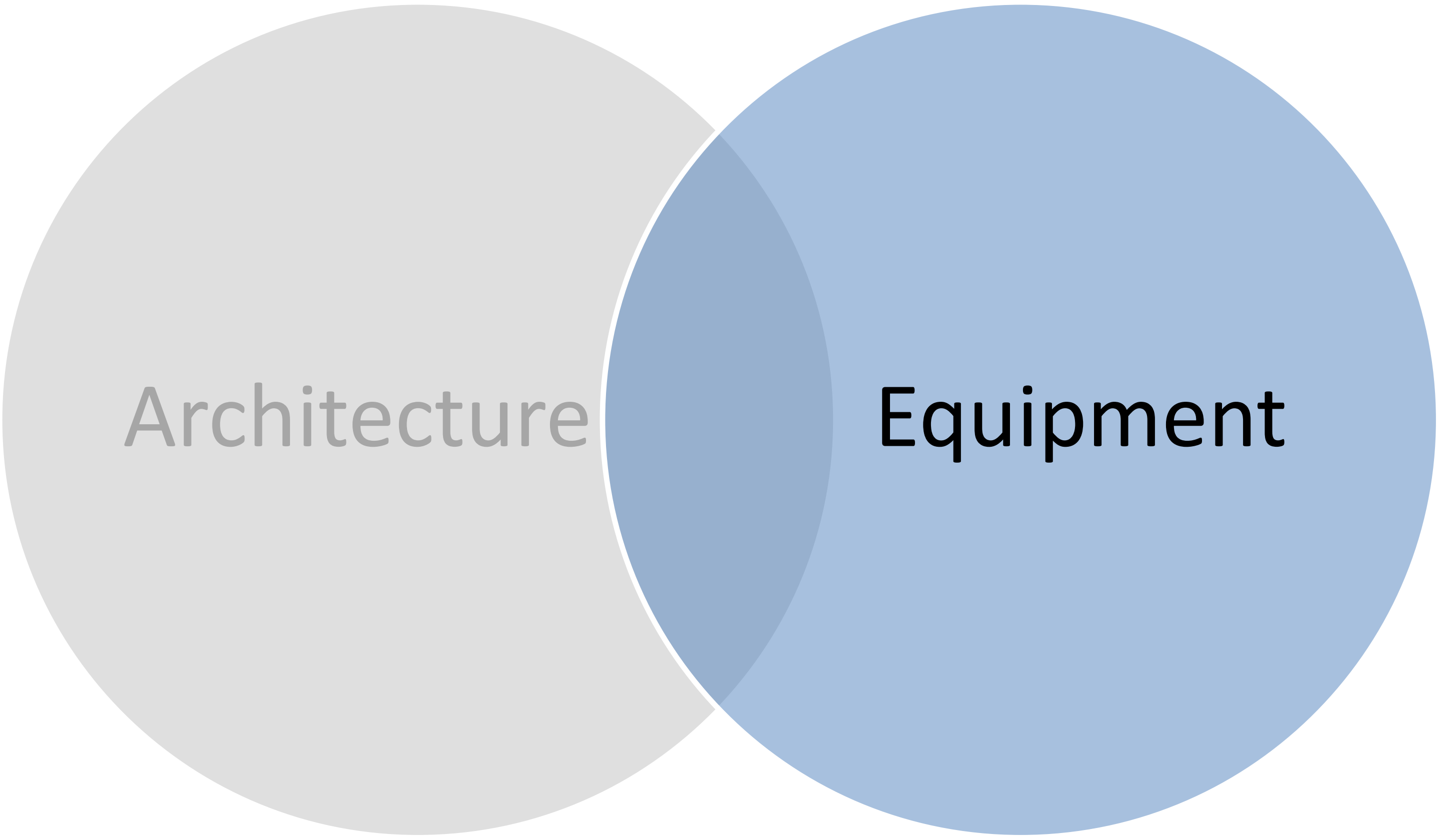
Windows offer visual occupant comfort, free light – at the cost of heat loss/gain

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





LSU AG Center


Architecture
Equipment

Equipment

UC SANTA BARBARA engineering

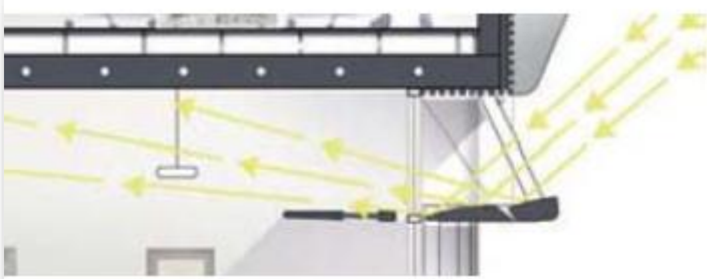
- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

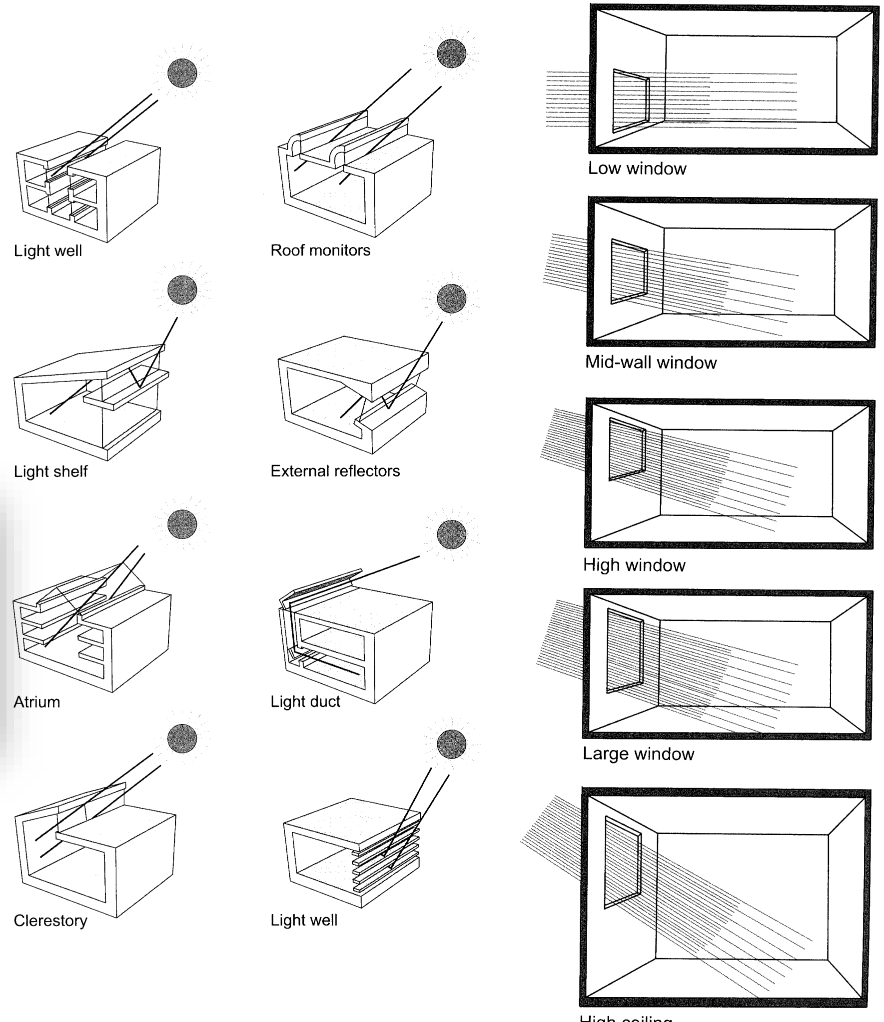
Equipment

- ❑ 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

Equipment

- ❑ Lighting
- ❑ **Ventilation**
- ❑ Heating
- ❑ Cooling

Ventilation needed for indoor air quality

Typically measured by Air Changes per Hour (ACH)

Environment	Rec. ACH
Office	4-6
Bar / Dining	12-30
Kitchens	15-60
Class 1 Clean room	~600

Foam Kote Inc

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

Equipment

UC SANTA BARBARA engineering

- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

<u>Natural Ventilation</u>

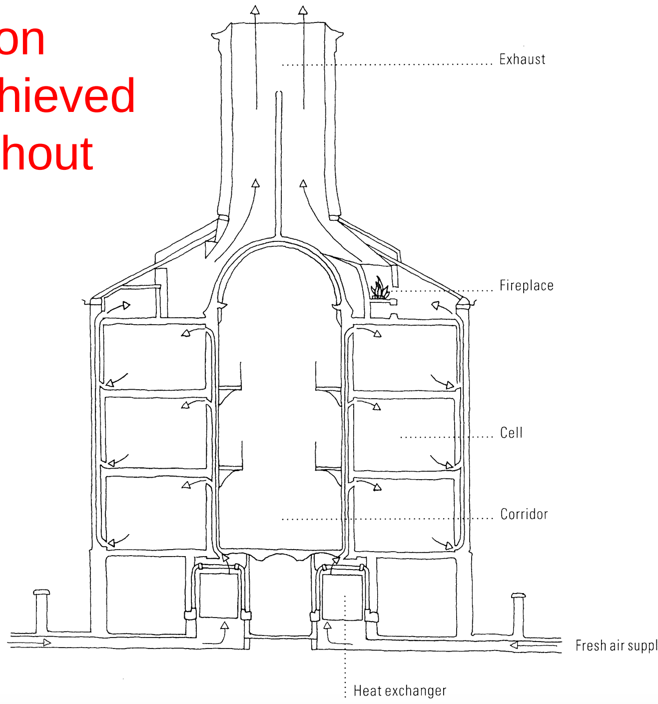
Has been used since ancient times

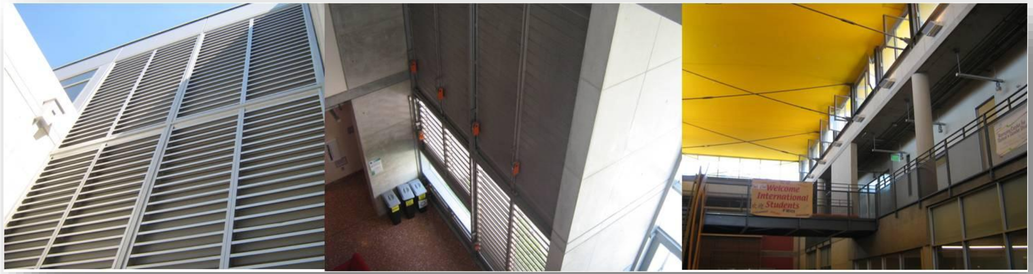
Works best in mild climates and tall buildings

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

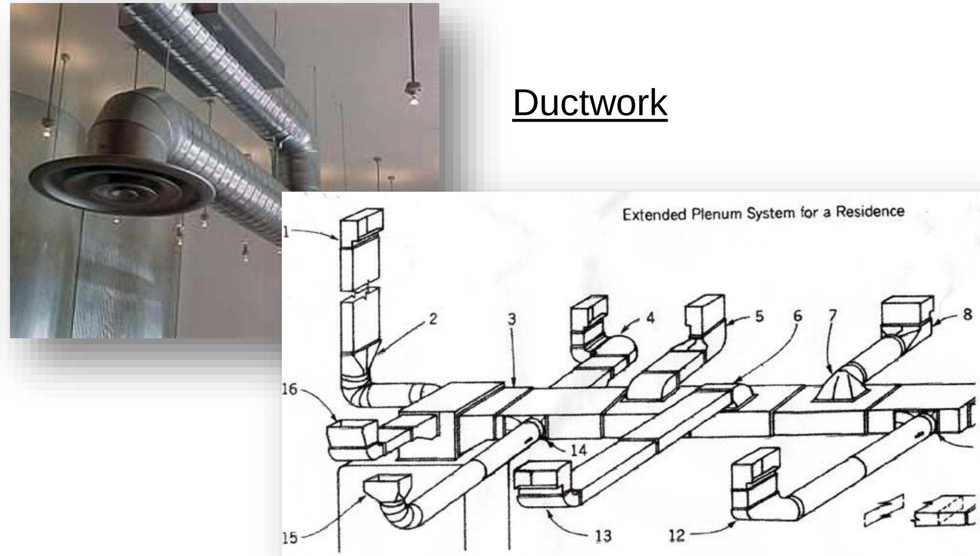
- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

<u>Ducted Ventilation</u>
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

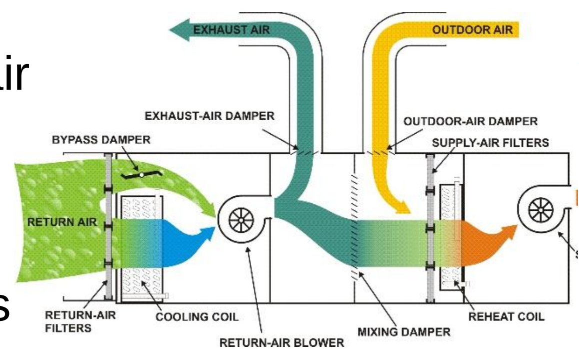
Management systems allow scheduling to throttle back flows for un-occupied hours

Nightime flush/ventilation an effective strategy



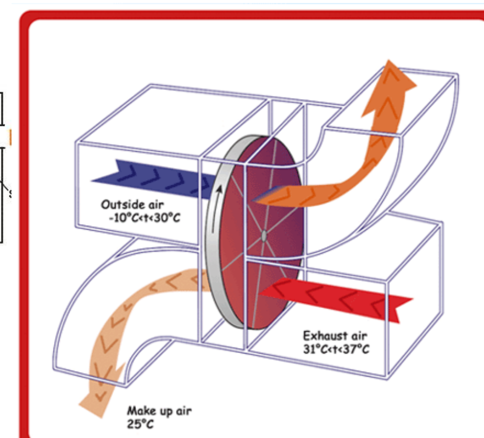
<u>Ductwork</u>

<u>Economizer</u>



Dectron

<u>Heat Recovery Wheel</u>

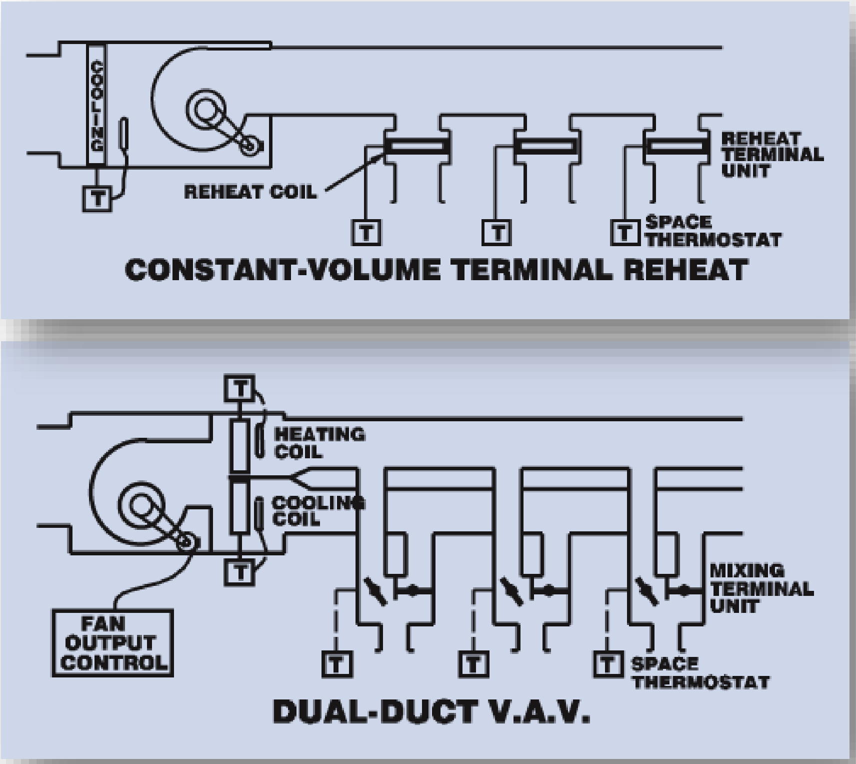


A diagram of a rotary heat exchanger, or "heat wheel" (From Uptime Technology BV)

datacenterknowledge.com

Equipment

- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling



Energybooks.com

Ducted Ventilation

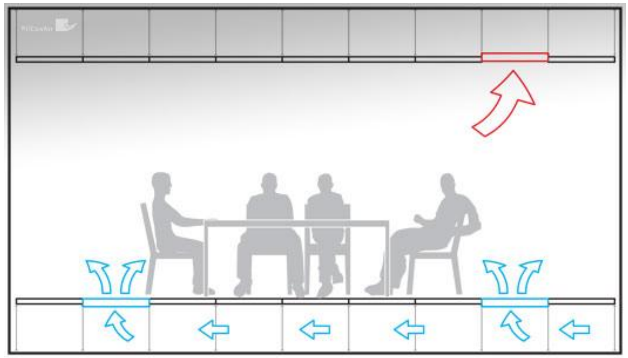
Single duct must use terminal reheat to satisfy different types of zones

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


Filconair

Equipment

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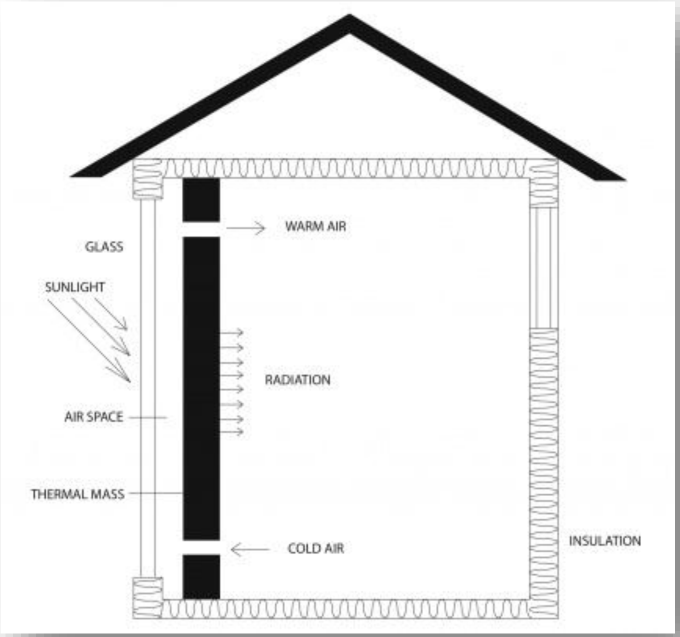
- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

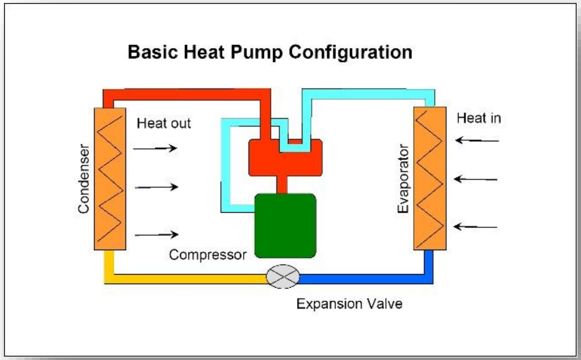
Heating can be obtained by passive measures including capturing solar energy

Energy intensive sources:
- Boiler
- District heating
- Heatpump
- Electric
- ….

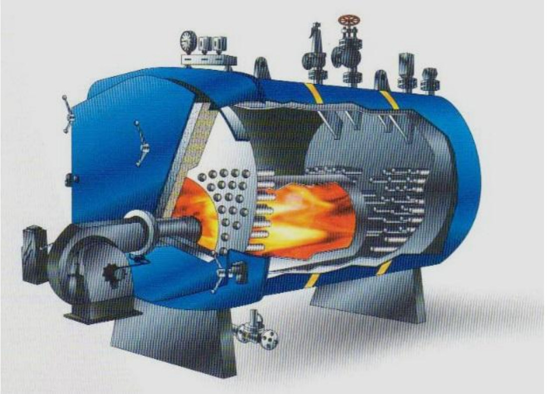
Trombe wall captures solar radiation



emmakpeirce



Energyalaska



Steamboiler.org

Equipment

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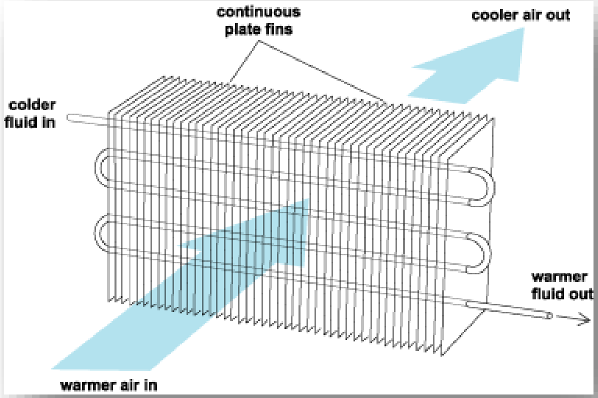
- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

Cooling can be achieved by similar methods (e.g. chiller machines)

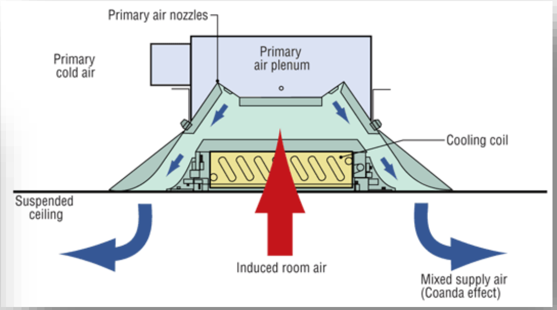
Chilled water distributed through piping throughout the building / district

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

Aircooledchillers.com



answers.com

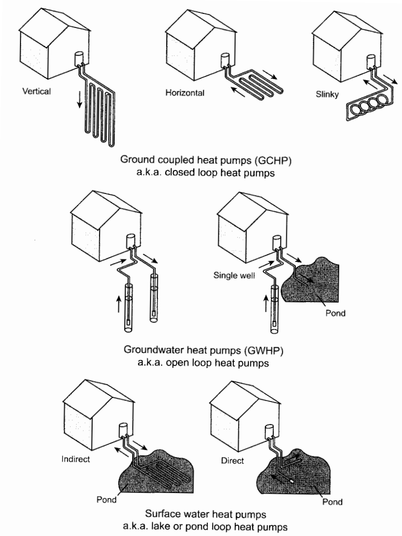


tacohydronics

Equipment

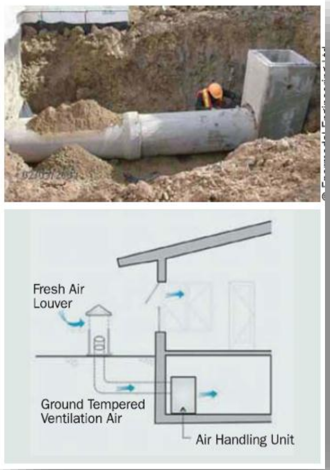
- ❑ Lighting
- ❑ Ventilation
- ❑ Heating
- ❑ Cooling

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



Fundamentals of Sustainable Buildings, Friedman

Ground source heat pumps, ducting gets free energy from ground



High Performance Buildings, Spring 2011

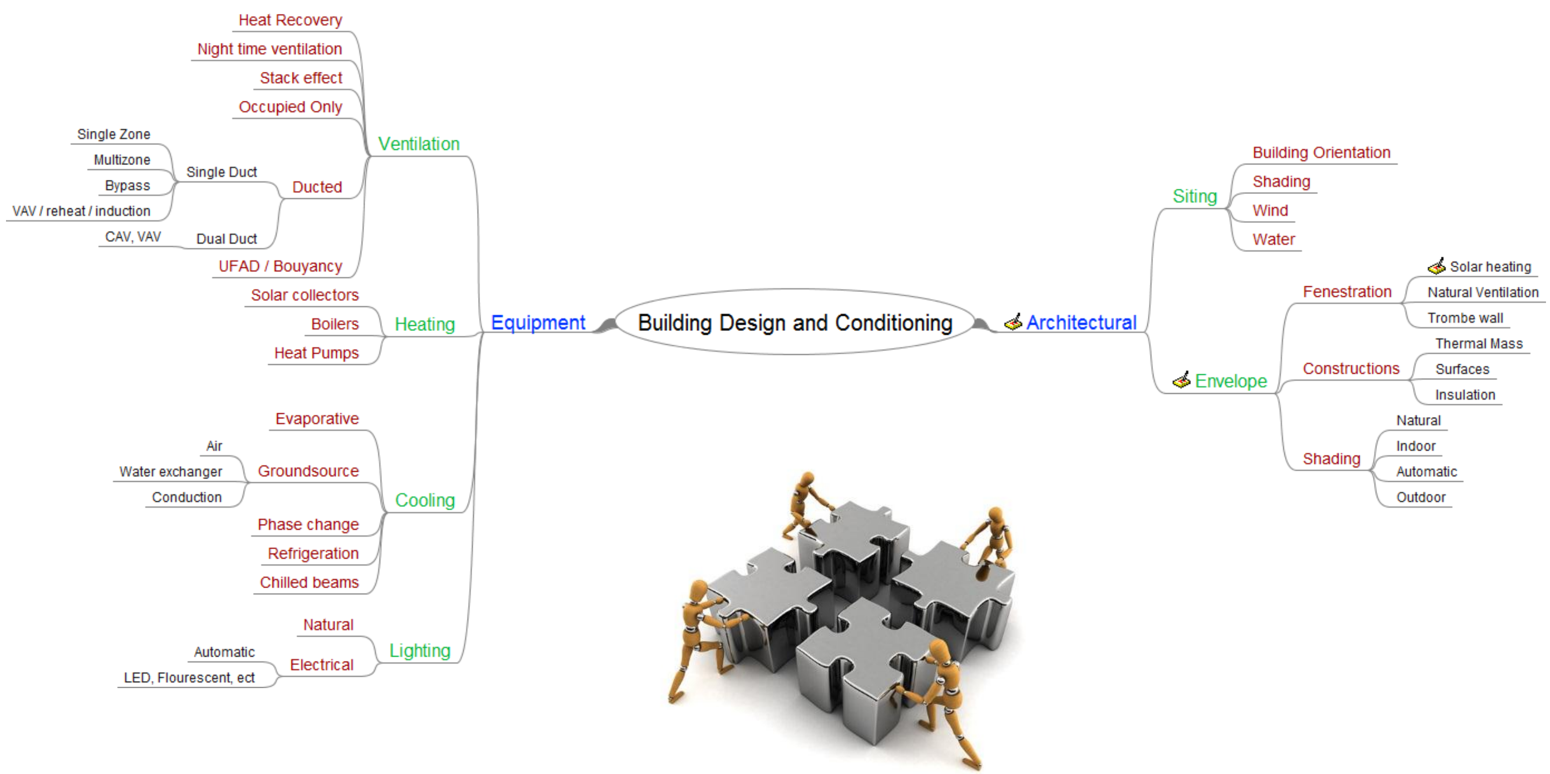
Phase change materials

specialtyfabricsreview

Phase change materials store energy for later times

climatetechwiki.org

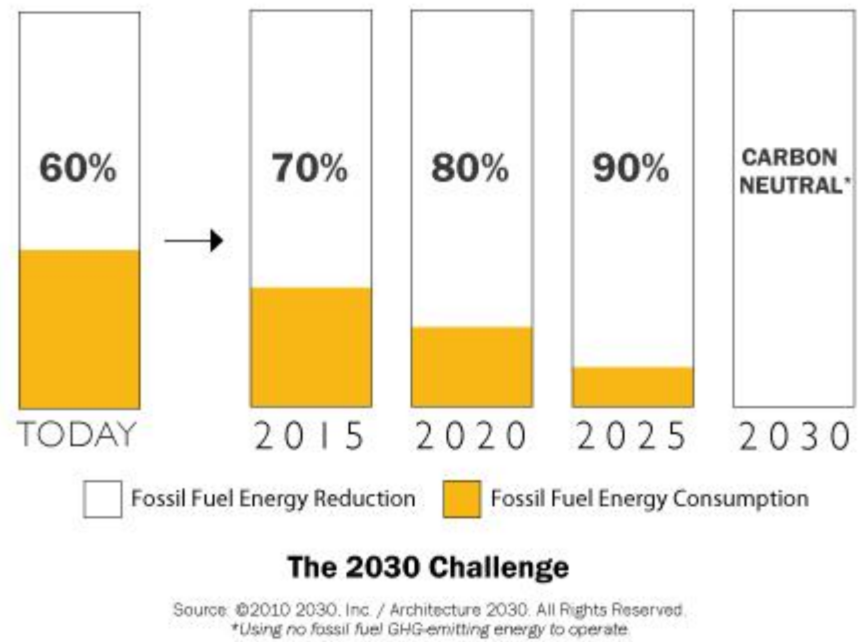
- Designing and equipping buildings is like a puzzle
- There are few products with as much hand-built and expert-experience involved in their production
- Nearly all buildings are one-off designs pulling together different pieces / design elements to form the puzzle

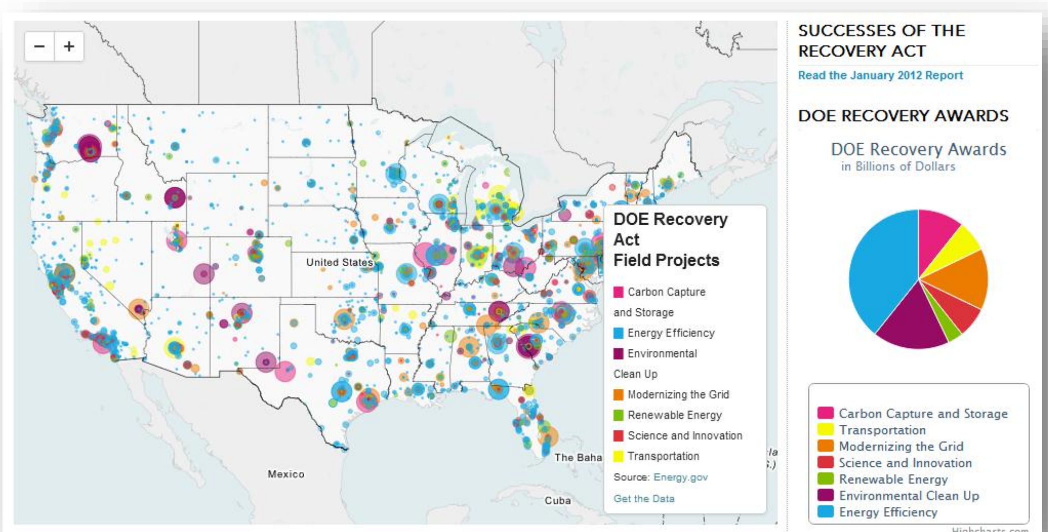


Can it be done?

Initiatives

Ed Mazria's challenge to get companies, govt, product manufactures to make Carbon Neutral Buildings by 2030





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

Examples

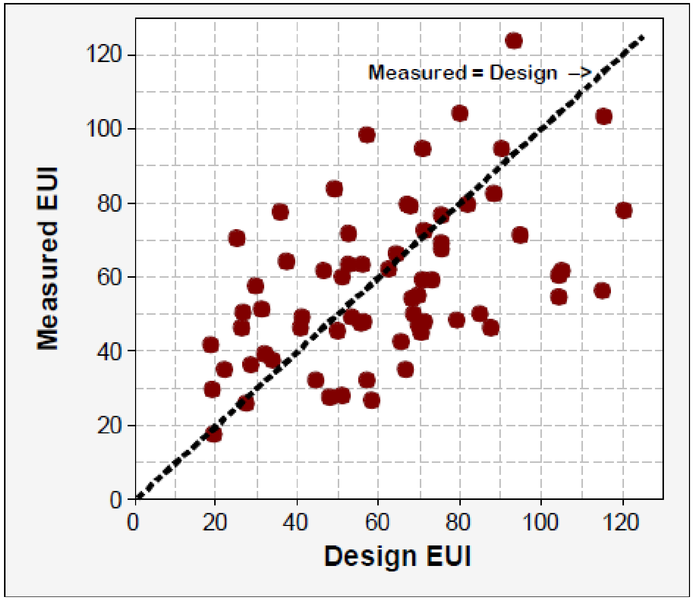
❑ It can be done! *(1-off examples)*

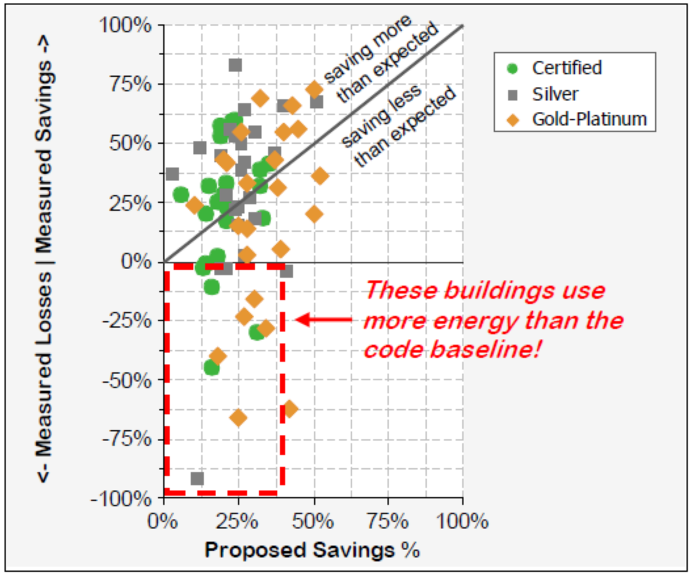
A Grander View, Ontario Canada
- 22Kft^2 office
- **80% Energy savings** as recorded in first year
- Most energy efficient office in CA

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





[Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.]

[Frankel 2008]

Pitfalls

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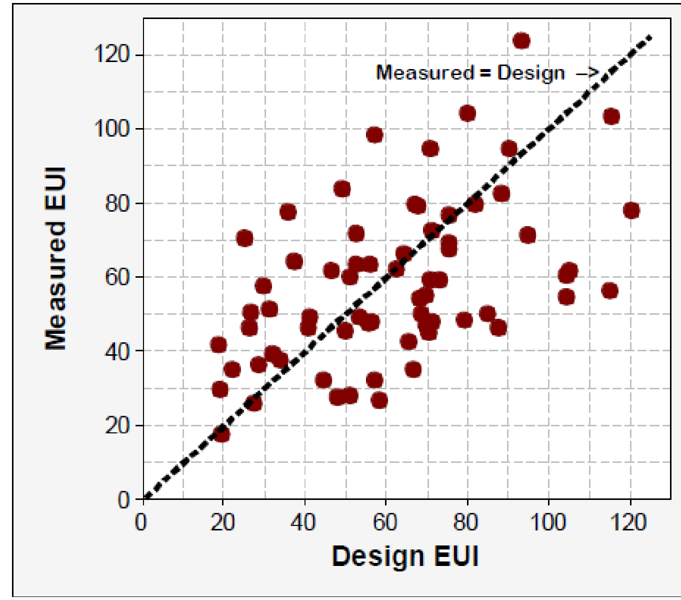
- "….these strategies must be applied together and properly integrated in the design and operation to realize energy savings. There is no single efficiency measure or checklist of measures to achieve low-energy buildings. "
- "… dramatic improvement in performance with monitoring and correcting some 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 "

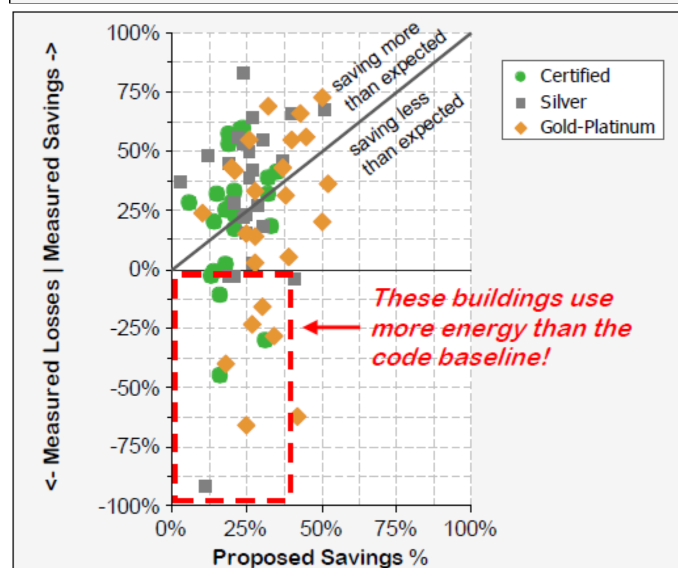
Modeling ←

Monitoring ←

Control ←

[Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.]





[Frankel 2008]

Systems - of - Systems

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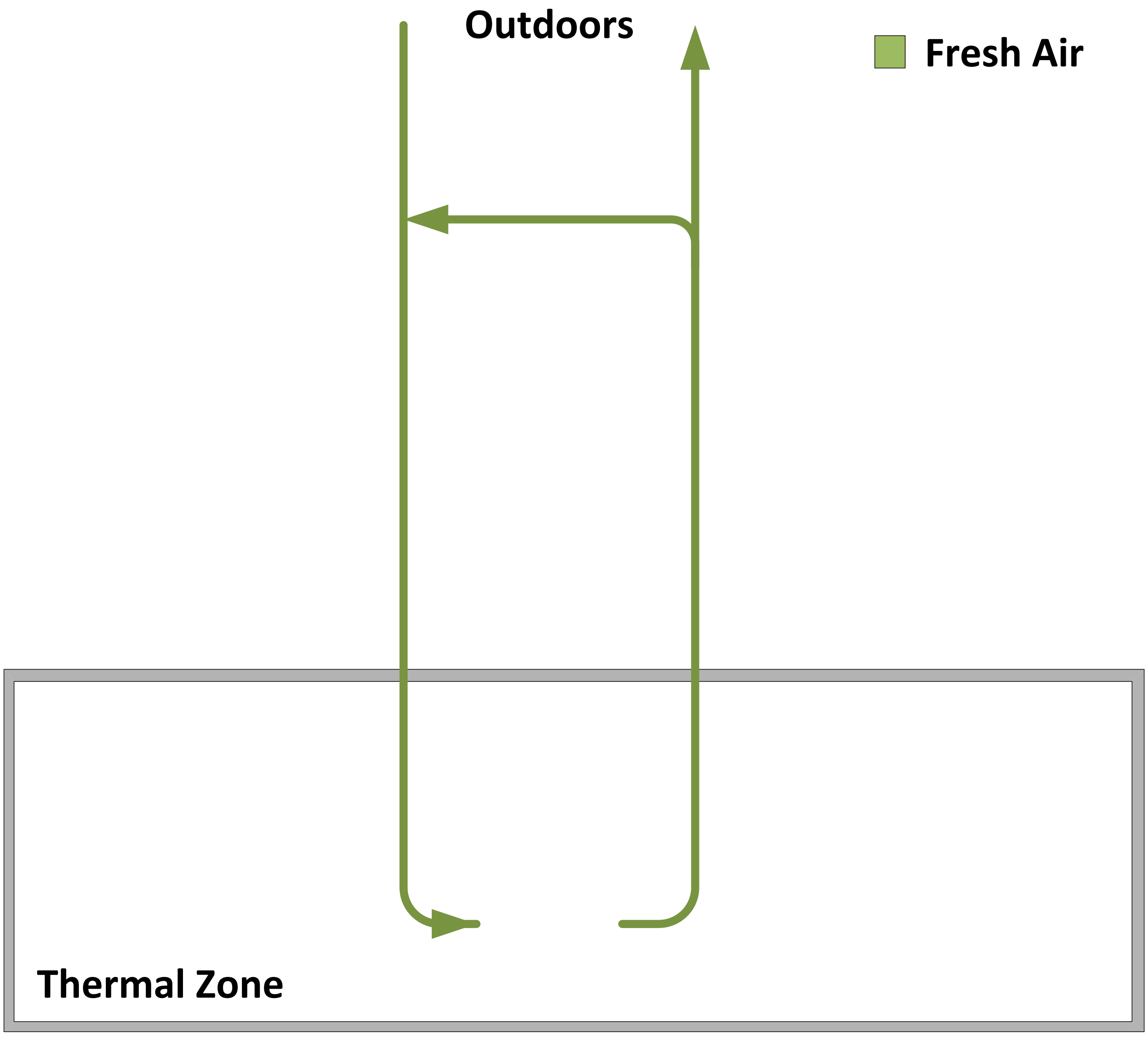
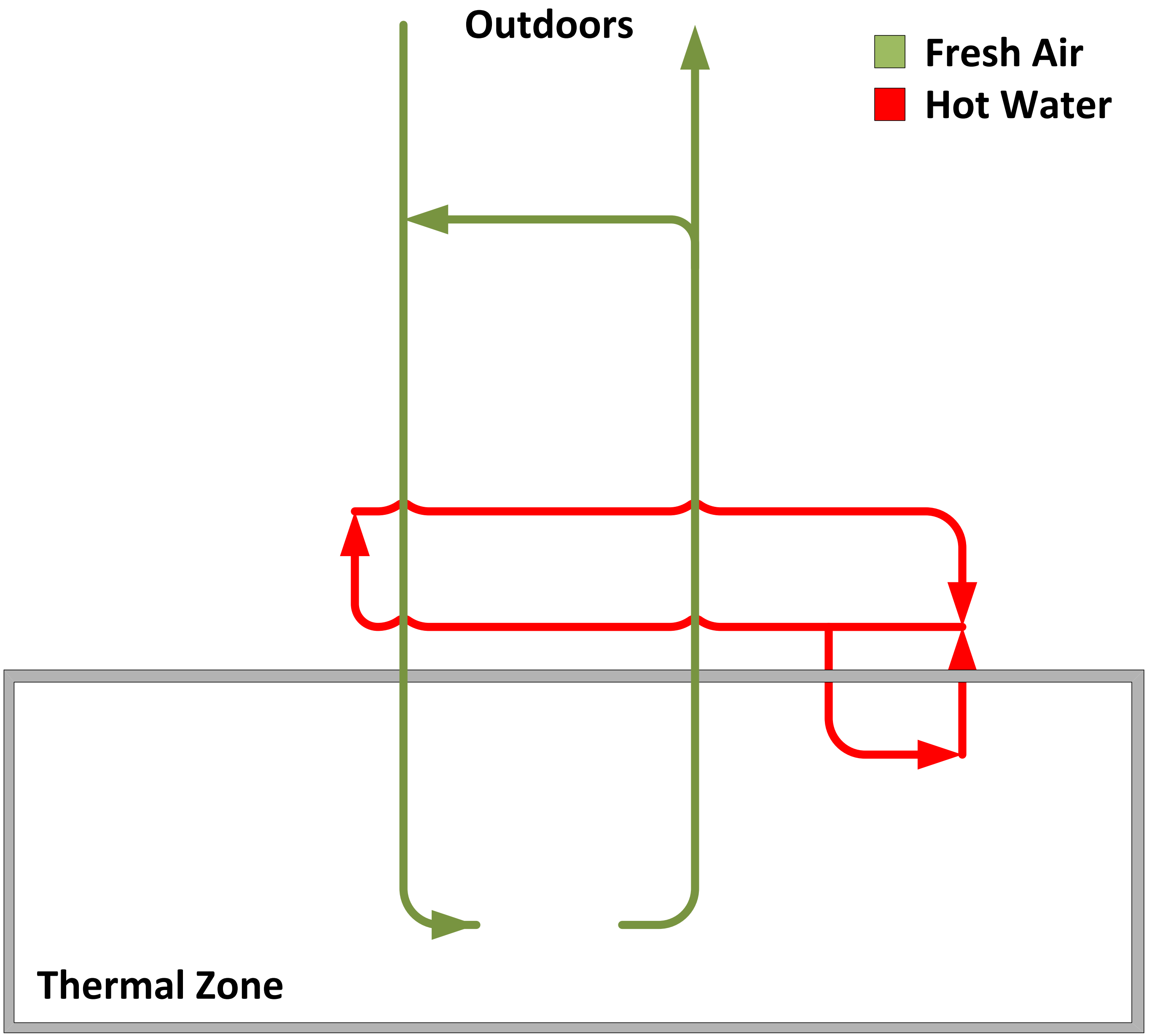


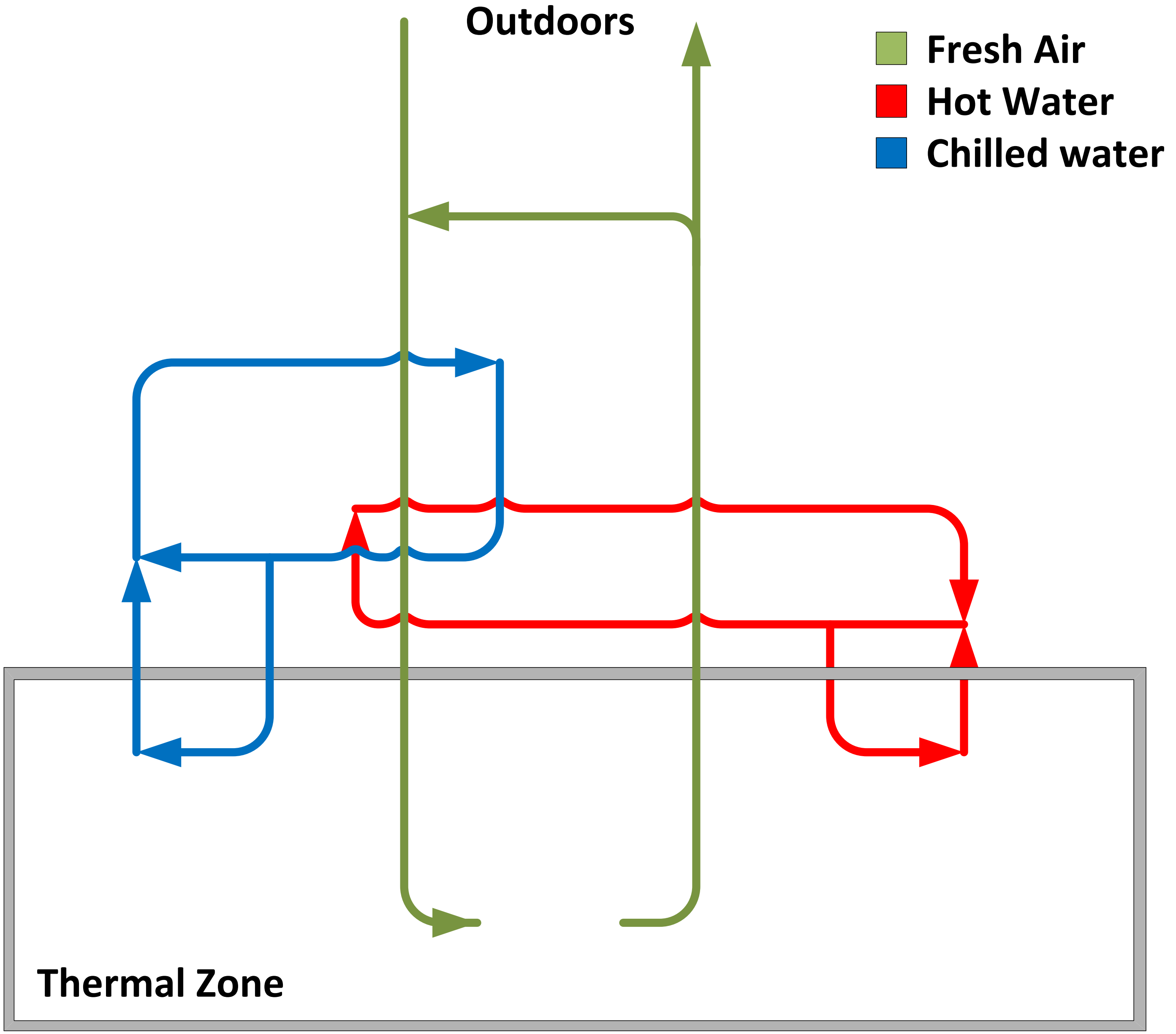
Systems - of - Systems

UC SANTA BARBARA engineering

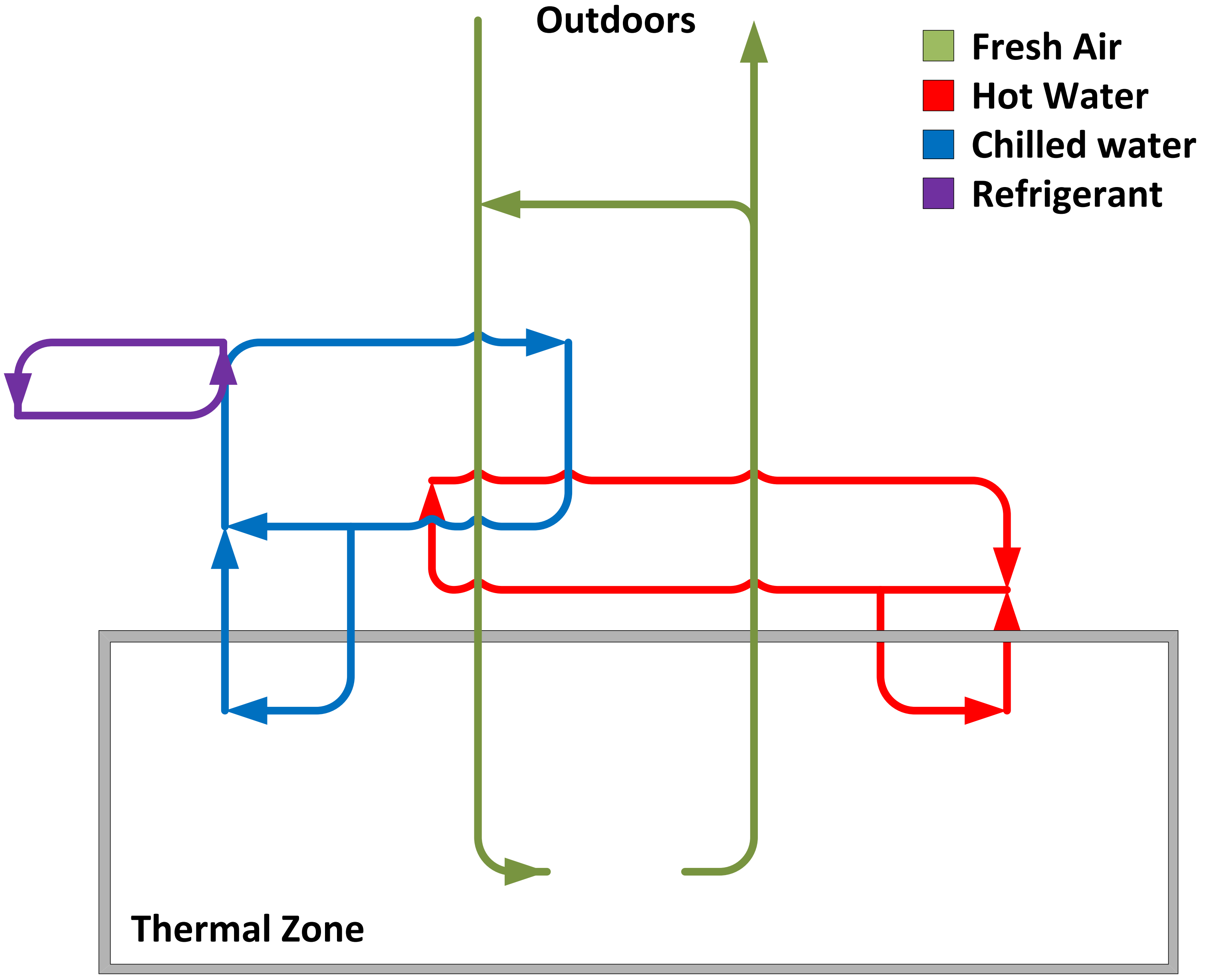


Systems - of - Systems

UC SANTA BARBARA engineering

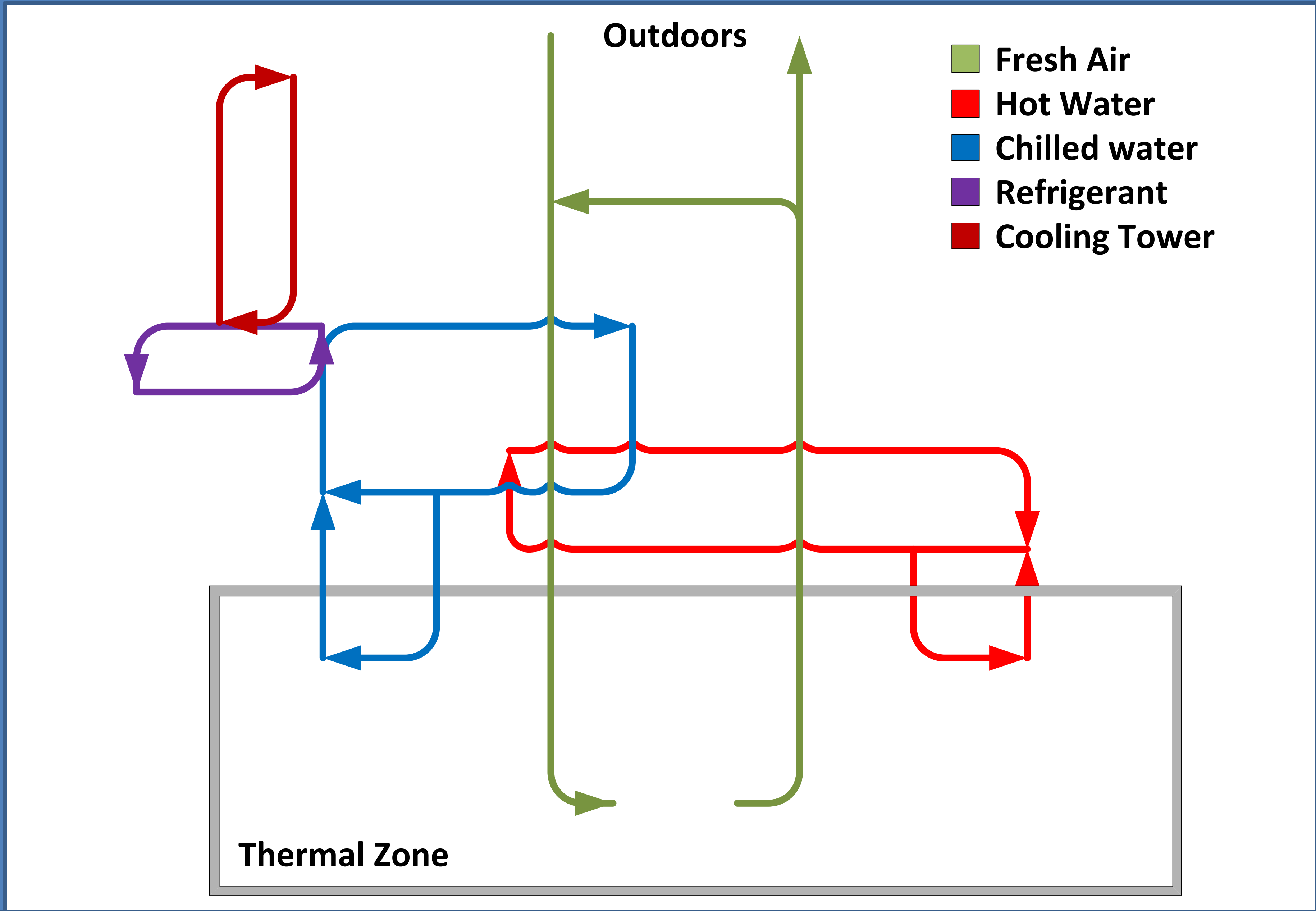


Systems - of - Systems



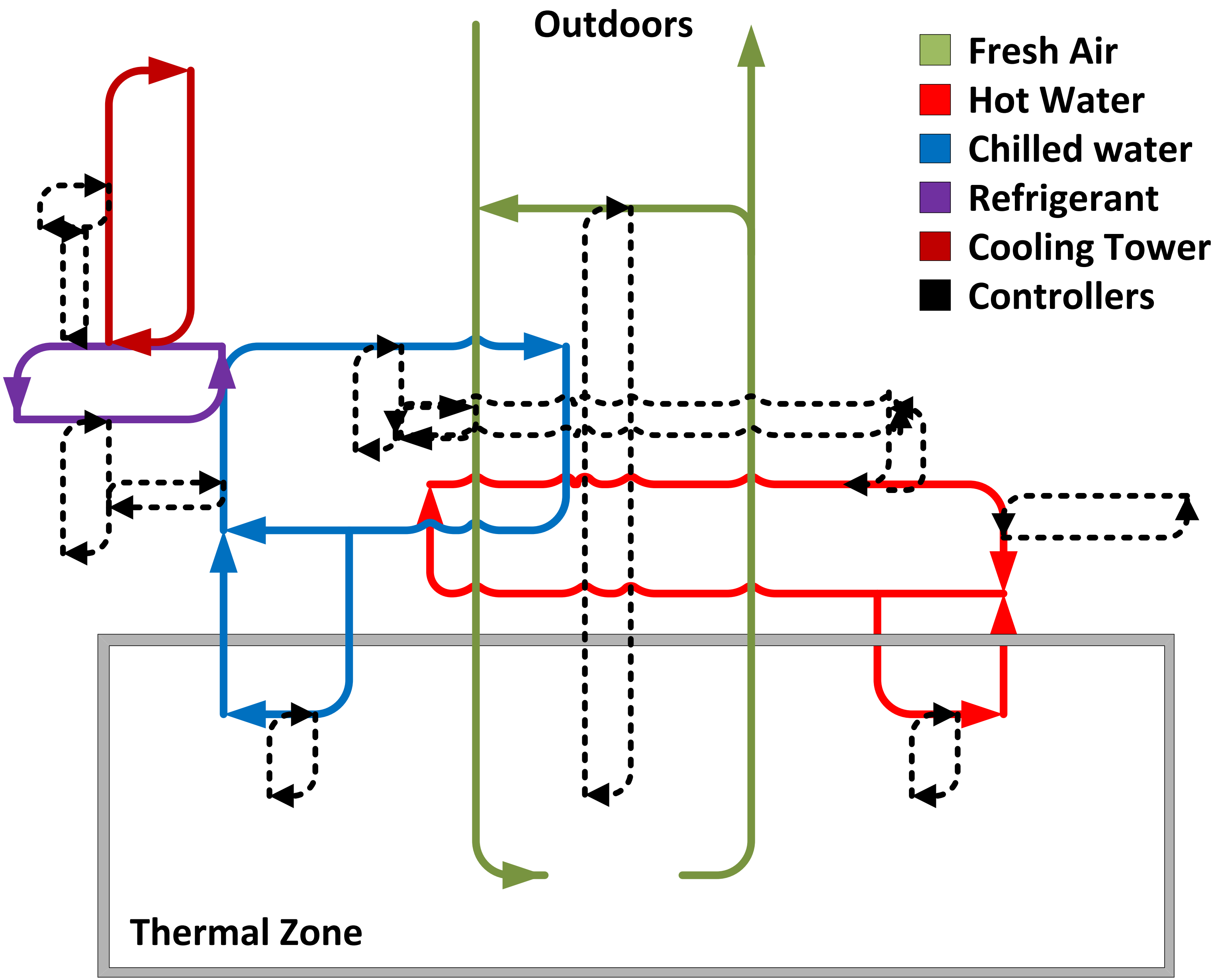
Systems - of - Systems

UC SANTA BARBARA engineering



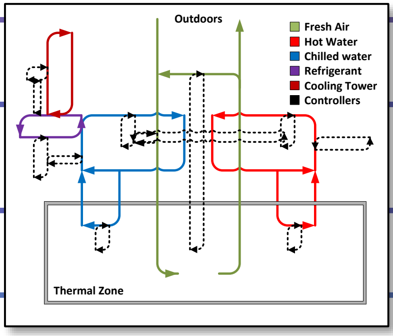
Systems - of - Systems

UC SANTA BARBARA engineering

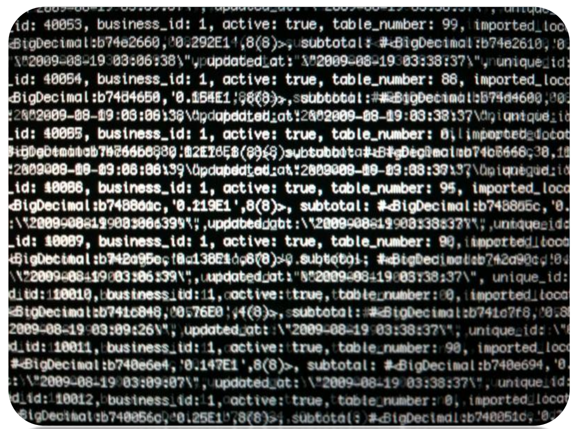


Systems - of - Systems

- 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

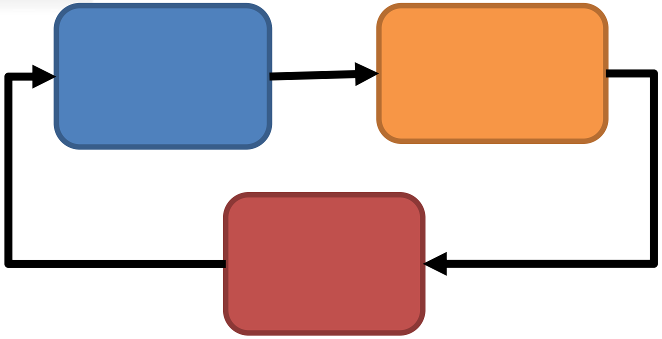


➢ Modeling



Data

Control



Energy Modeling - Choices

Space (larger)

TRNSYS

EnergyPlus

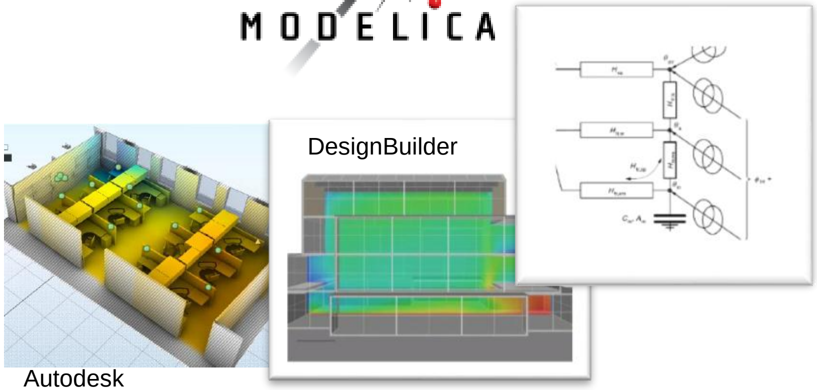
DOE-2

eQUEST

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

MODELICA

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



Time (faster)

Energy Modeling – Uses

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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
- ....

U.S. GREEN BUILDING COUNCIL LEED USGBC ™

Energy Modeling & Uncertainty

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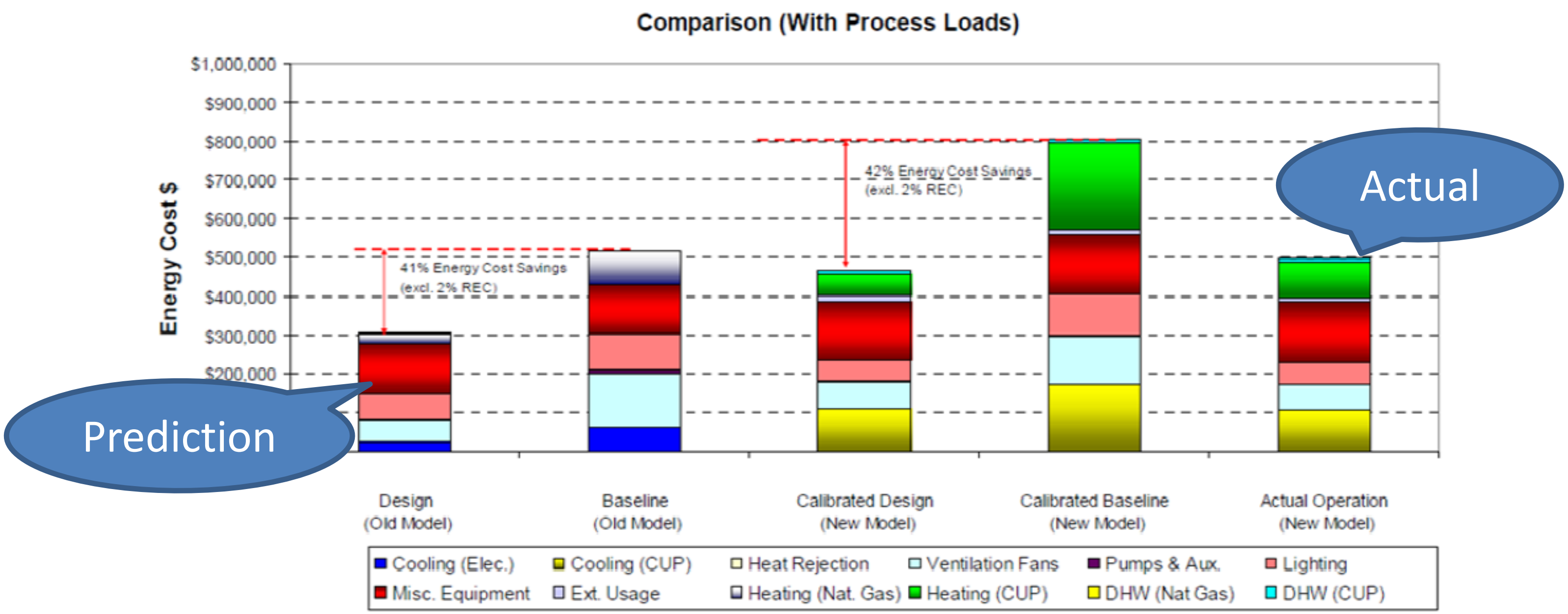
- ❑ Decades spent on developing energy models
  - ➢ Most are validated on a component basis
- ❑ At the systems level, the most advanced energy models, are still do not predict consumption accurately during the design stage



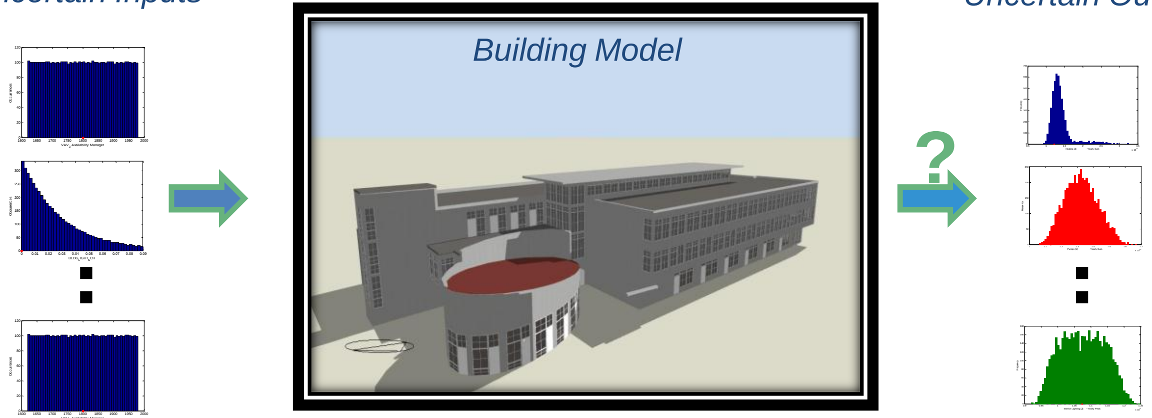
* Stanford Y2E2 Building

UQ in Buildings - Flow

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

Uncertain Inputs

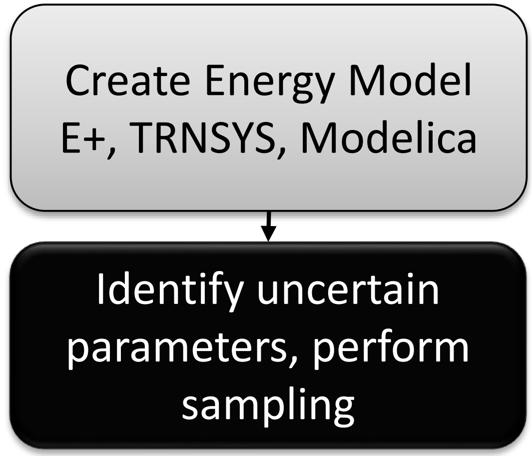
Uncertain Outputs



O(1000)

O(10)

- Create Energy Model E+, TRNSYS, Modelica
- Identify uncertain parameters, perform sampling
- Perform numerous simulations, pre-process output
- Calculate full order meta-model
- Analysis (SA, opt, calib, FMEA, …)


Create Energy Model
E+, TRNSYS, Modelica
Identify uncertain parameters, perform sampling

Parameter Variation

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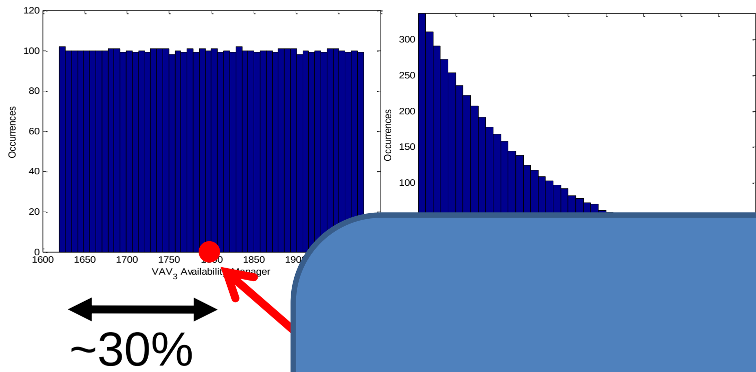
All numerical design & operation scenario (DOS) parameters in the model are varied concurrently (not architectural design)



The Harmonisation of Thermal Properties of Building Materials
J A Clarke[1], P P Yaneske[1] & A A Pinney[2]
(1) Energy Simulation Research Unit, Department of Architecture and Building Science, University of Strathclyde, (2) Building Research Establishment, Watford.

Quantifying the Effects of Uncertainty in Building Simulation

Iain Alexander Macdonald B.Sc., M.Sc.

A thesis submitted for the Degree of Doctor of Philosophy

Department of Mechanical Engineering
University of Strathclyde

July 2002

Distribution types are

- Parameters varied 30% their mean
- Some paran 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!

	s
	c
	eters etc
Water Loop	Pumps
Terminal unit	VAV box, chilled beam, radiant heating floor
Zone external	Envelope, outdoor conditions
Zone internal	Usage, internal heat gains schedule,
Zone setpoint	Zone temp setpoint
Sizing parameter	Design parameters for zone, system, plant

Parameter Sampling

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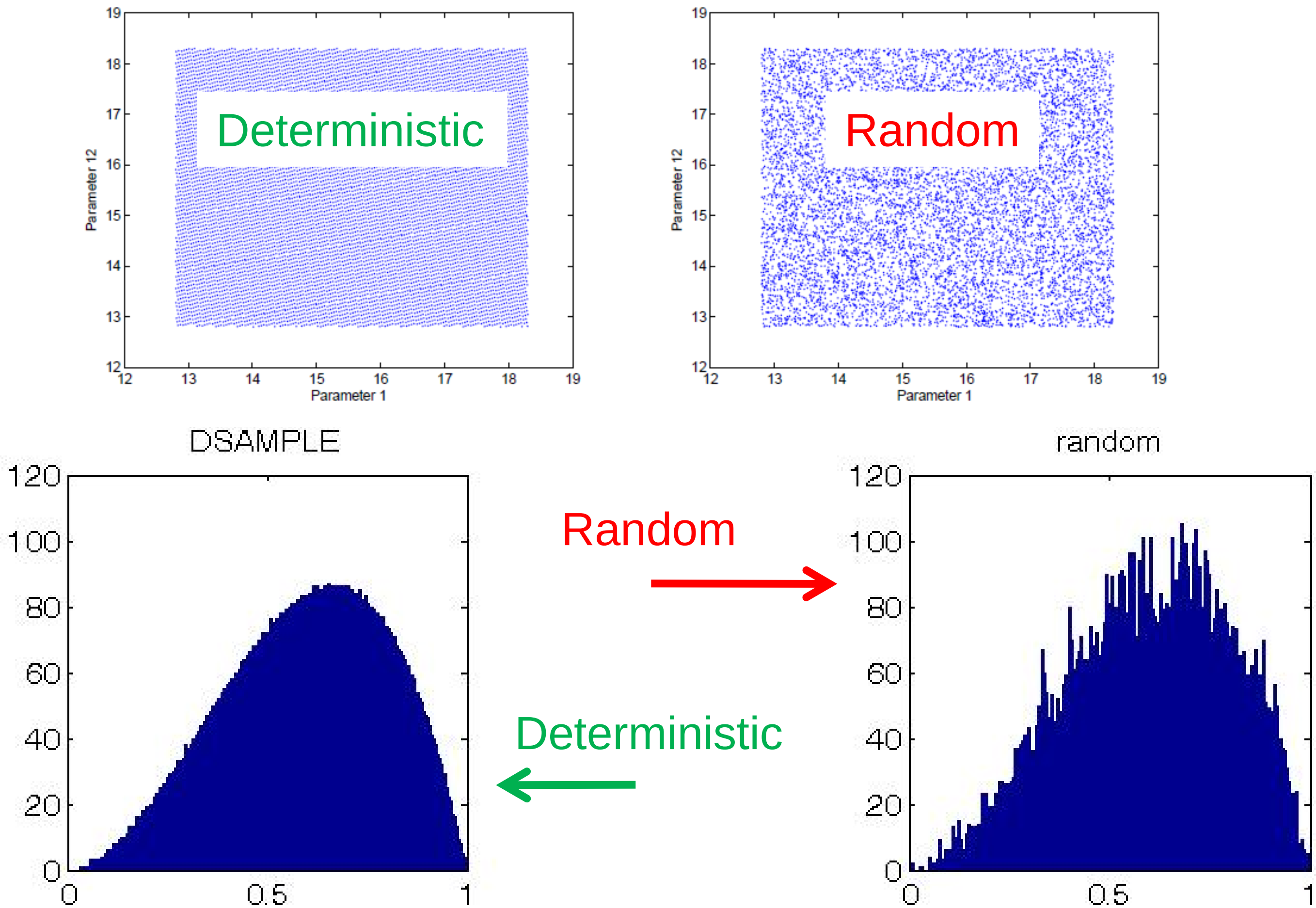
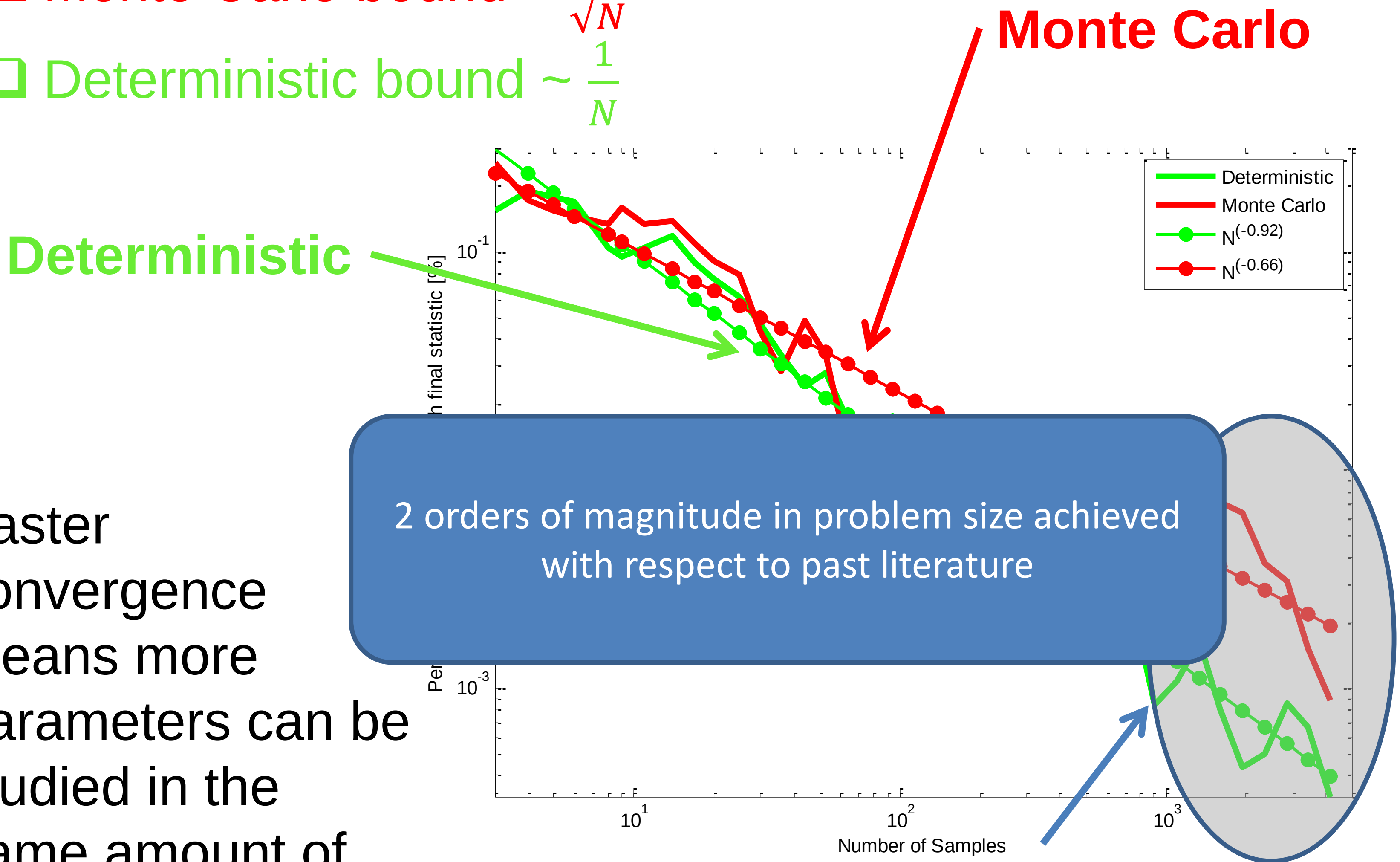
engineering

- ❑ Monte-Carlo(random) = clumps
- ❑ Deterministic = uniformly ergodic



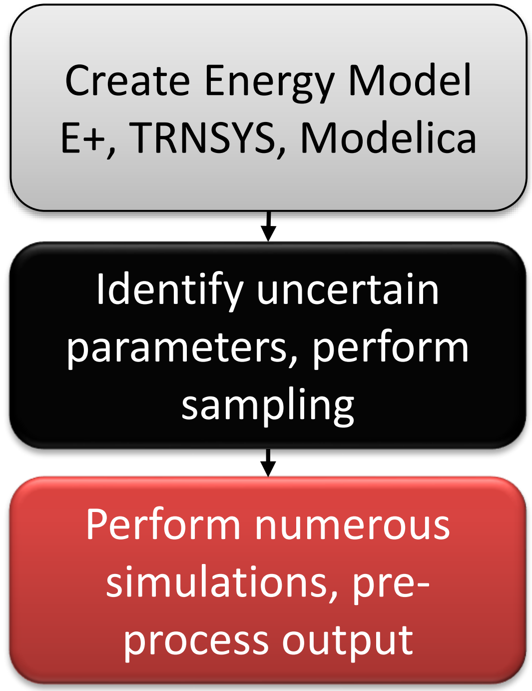
Convergence Properties

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



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

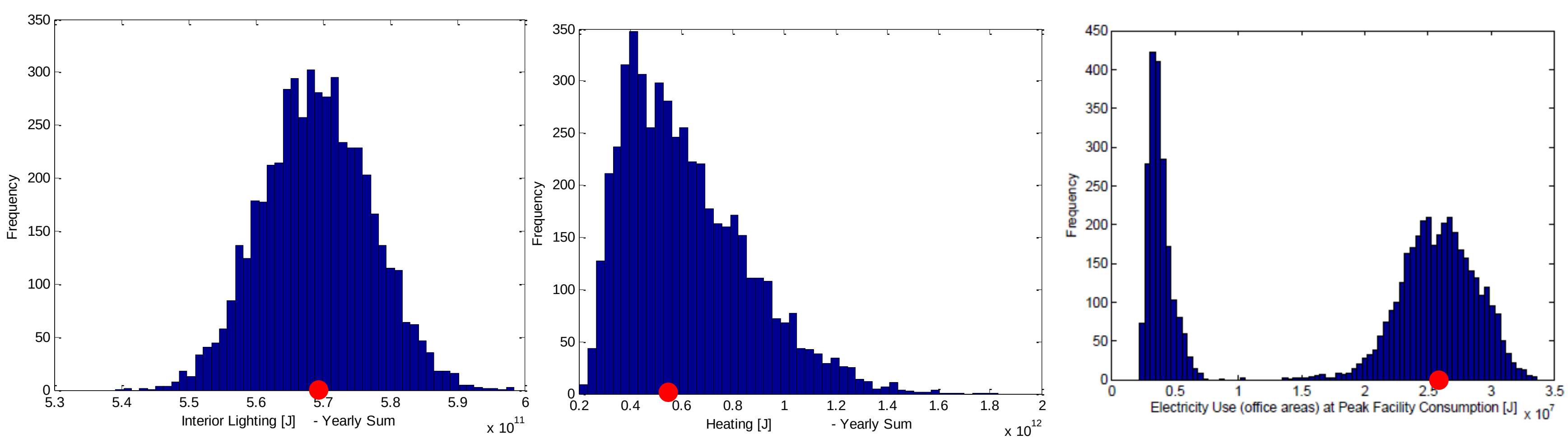
Biggest difference between MC & Deterministic is when N is large


Create Energy Model
E+, TRNSYS, Modelica
Identify uncertain parameters, perform sampling
Perform numerous simulations, pre-process output

Typical Output Distributions

Facility and Submetered Outputs
+ Comfort
+ Gas Facility
+ Electricity Facility
Thermal Comfort
Heating
Cooling
Pump
Fan
Interior Lighting
Interior Equipment

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



* TRNSYS results

Model Results - UQ

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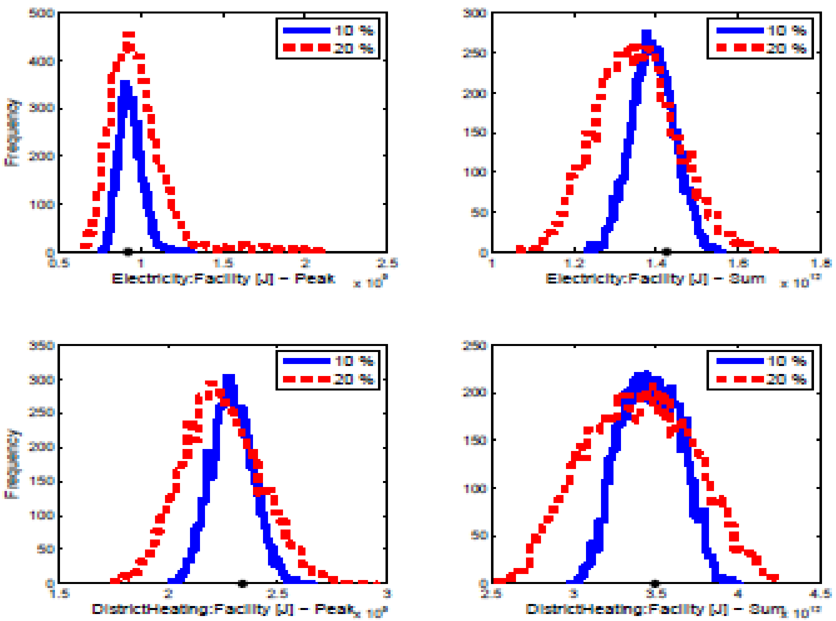
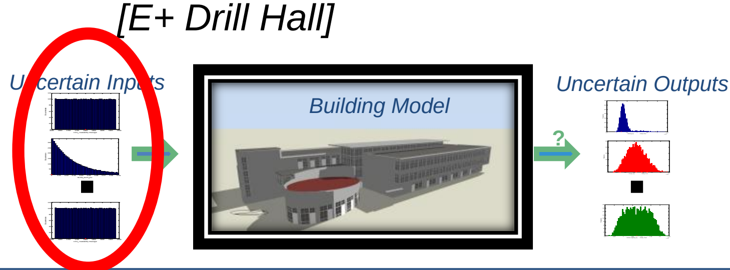
Characteristics of the output based on *different inputs*

Influence of Different Parameter Variation size

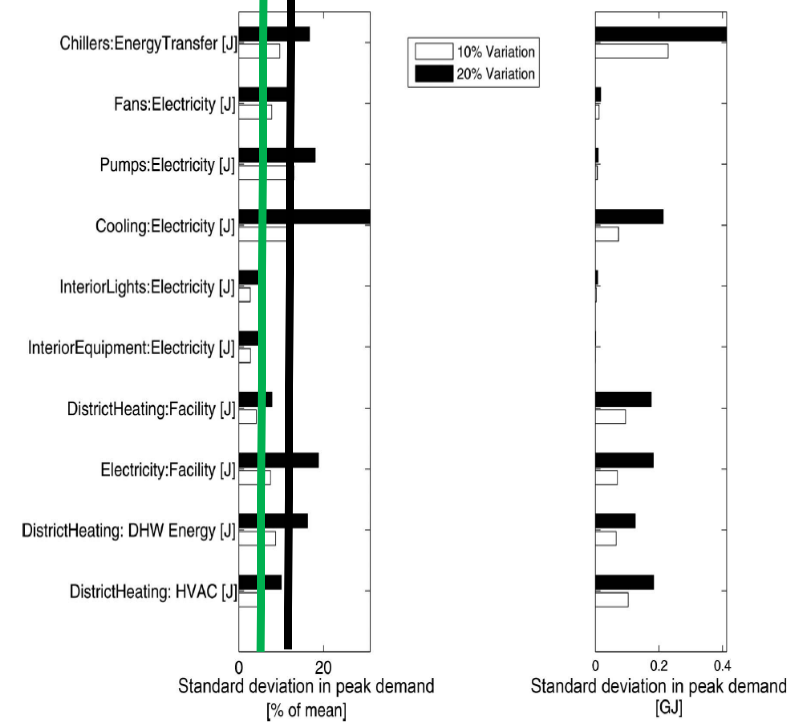


[E+ Drill Hall]



Input Uncertainty @ 10%

Input Uncertainty @ 20%



Model Results - UQ

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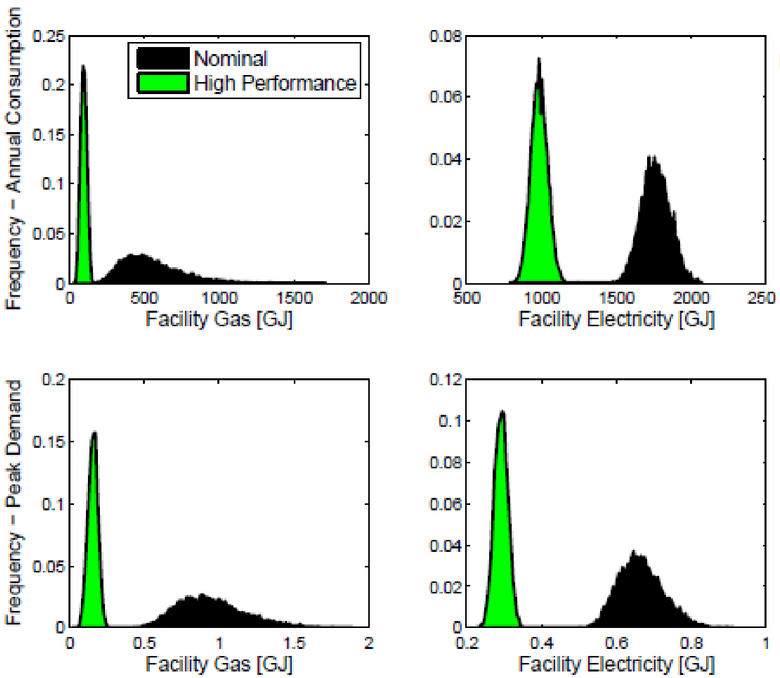
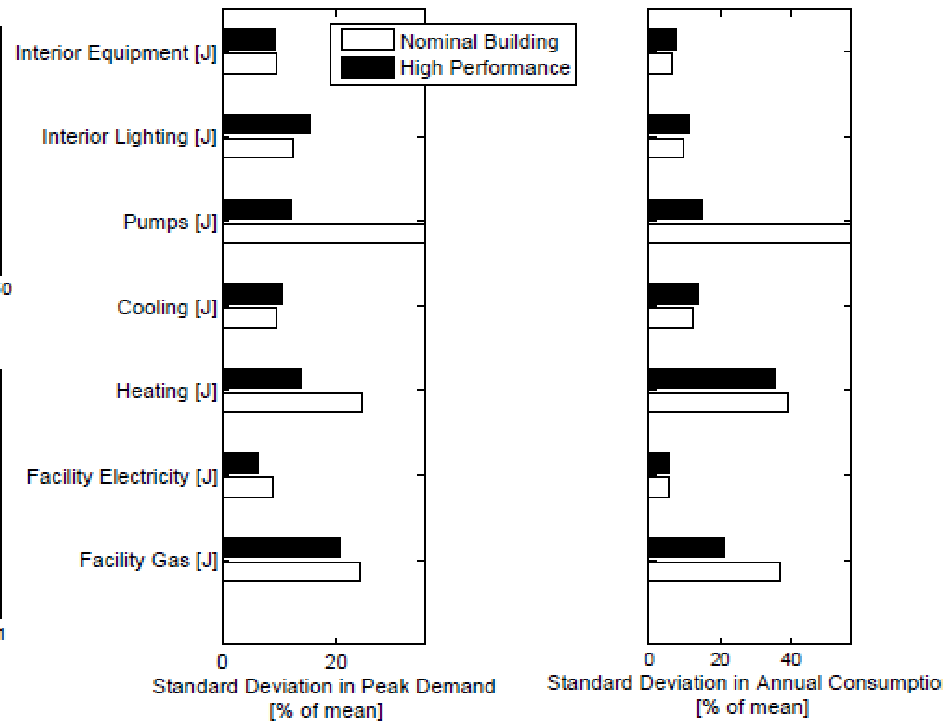
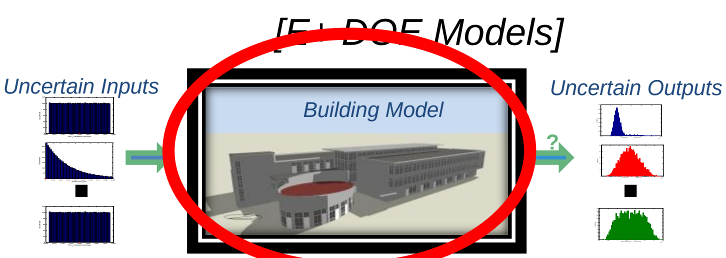
Characteristics of the output are considered based on *different designs*

Nominal vs. High Efficiency Design

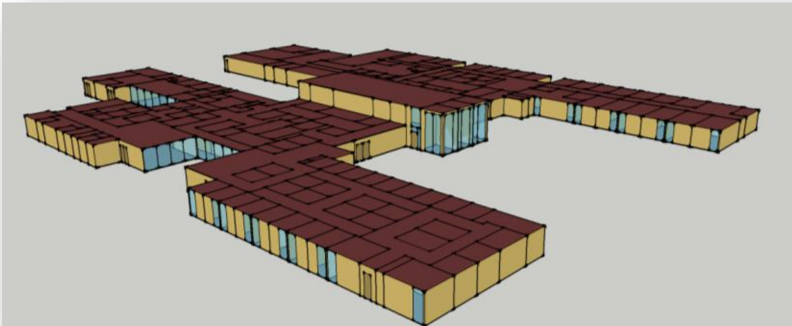






B. Eisenhower, et al. A COMPARATIVE STUDY ON UNCERTAINTY PROPAGATION IN HIGH PERFORMANCE BUILDING DESIGN *International Building Performance Simulation Association, BuildSim 2011*

UQ in Dynamics



Detailed Whole-Building Model

Detailed Energy Software

EnergyPlus

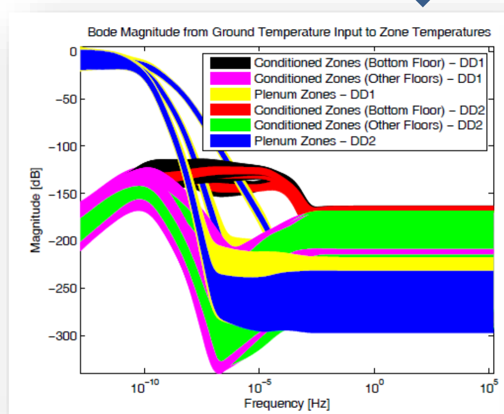
$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{surfaces}} \dot{Q}_{conv_i} + \sum_{i=1}^{N_{zones}} \dot{Q}_{mixing_i} + \sum_{i=1}^{N_{sl}} \dot{Q}_{sl_i} + \dot{Q}_{inf_z} + \dot{Q}_{HVAC_z},$$

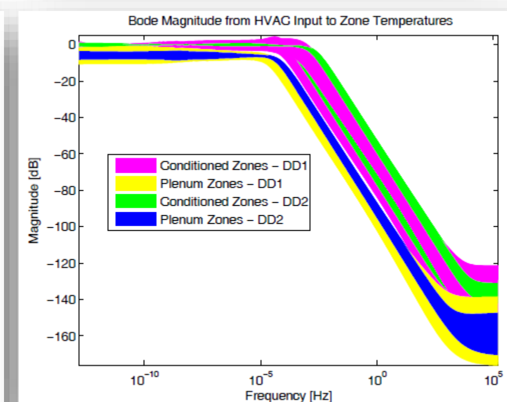
$$\dot{x} = A(x_0, p)x + B_u(x_0)u + B_w(x_0, p)w$$
$$y = Cx$$

Analytic Linear Meta-model

Uncertainty in closed loop performance

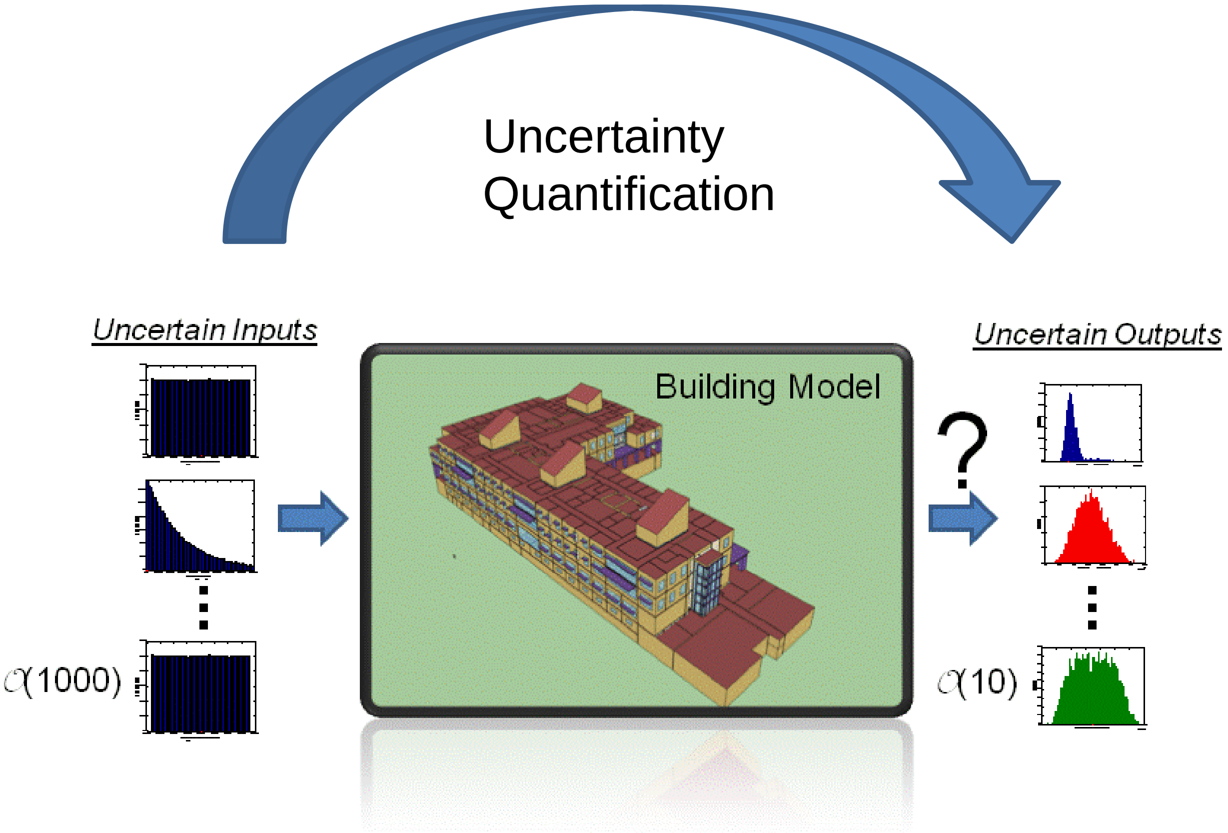
771 Physical parameters with uncertain bounds





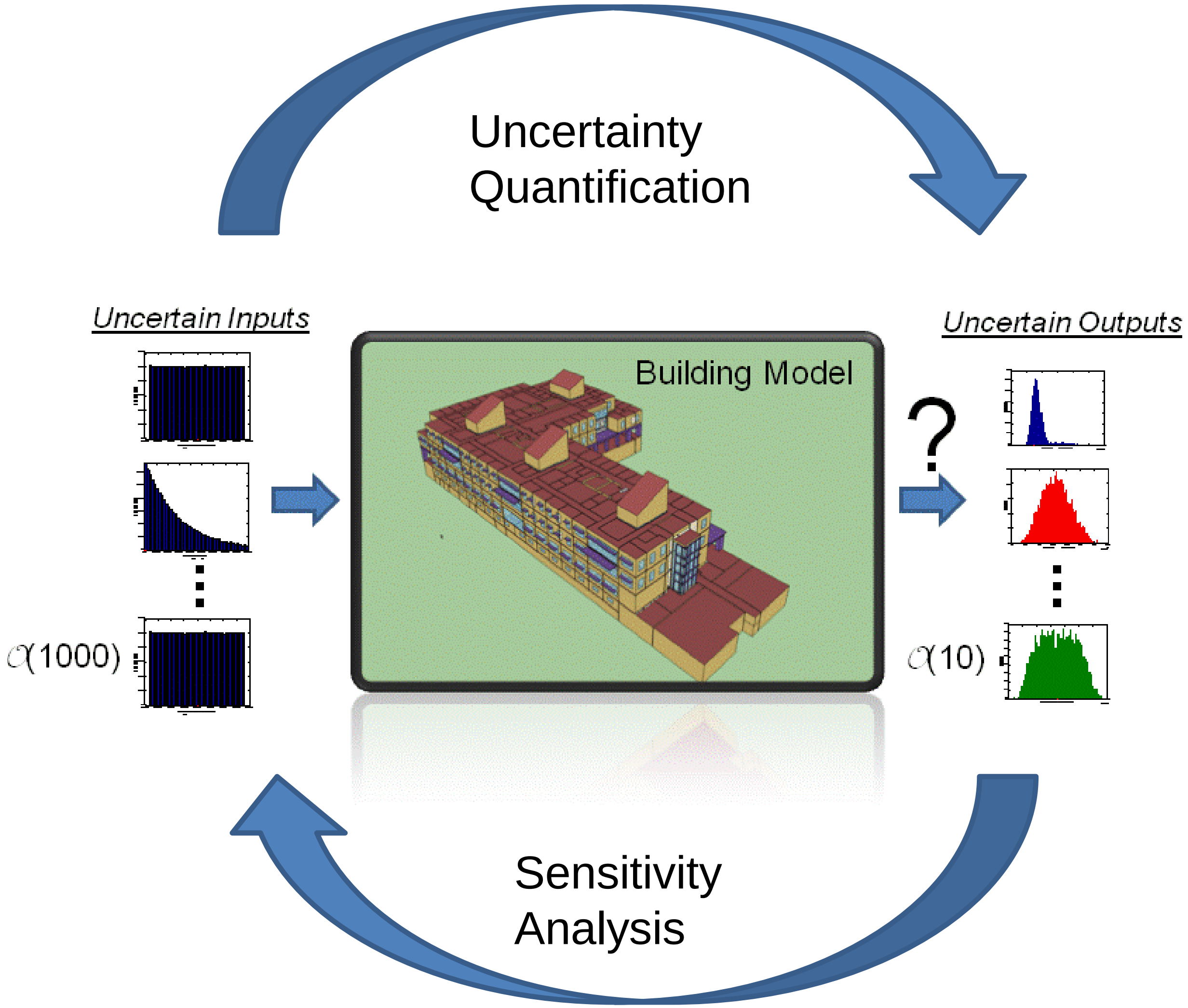
Eisenhower, et al. EXTRACTING DYNAMIC INFORMATION FROM WHOLE-BUILDING ENERGY MODELS, ASME Design for Dynamics 2012

Sensitivity Analysis



Sensitivity Analysis

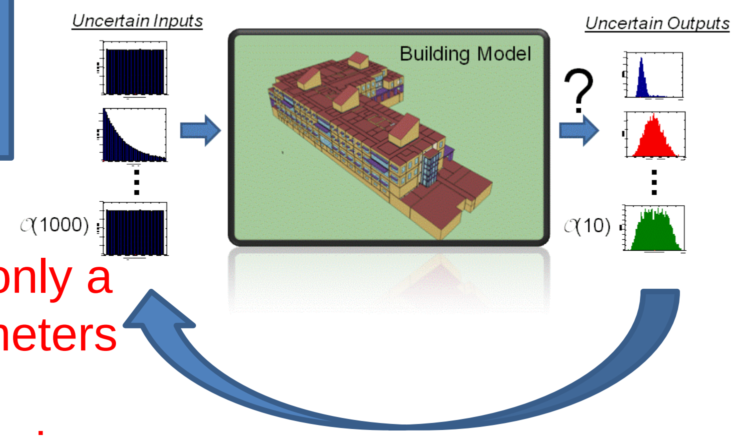
UC SANTA BARBARA engineering

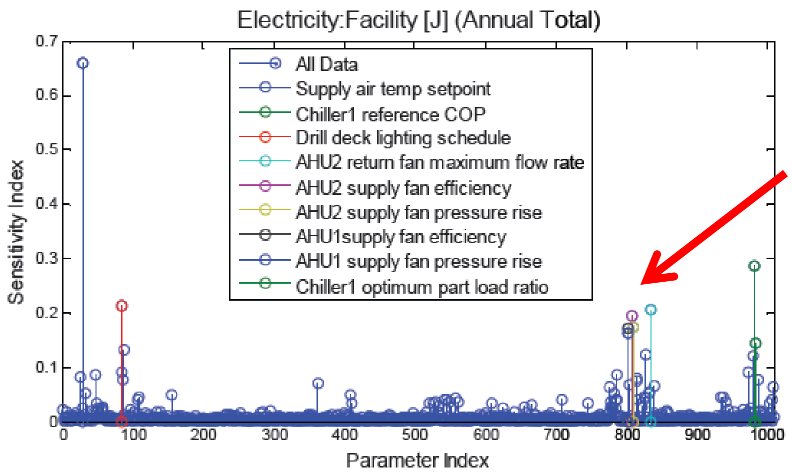


Sensitivity Analysis

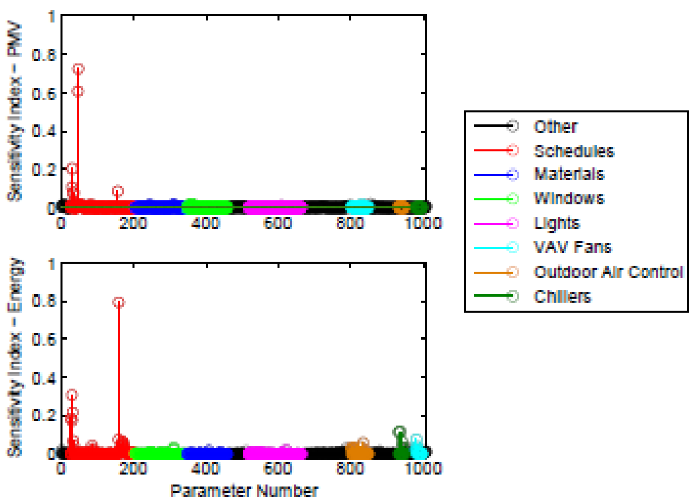
UC SANTA BARBARA engineering

Identifying key parameters in a building helps in design optimization, continuous commissioning, model calibration, …

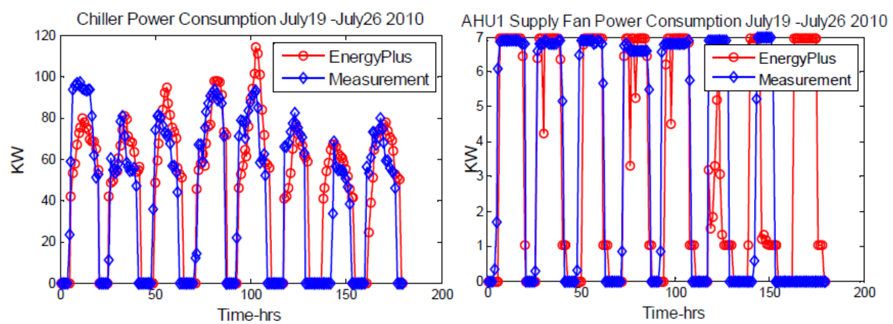




Typically only a few parameters drive uncertainty in output

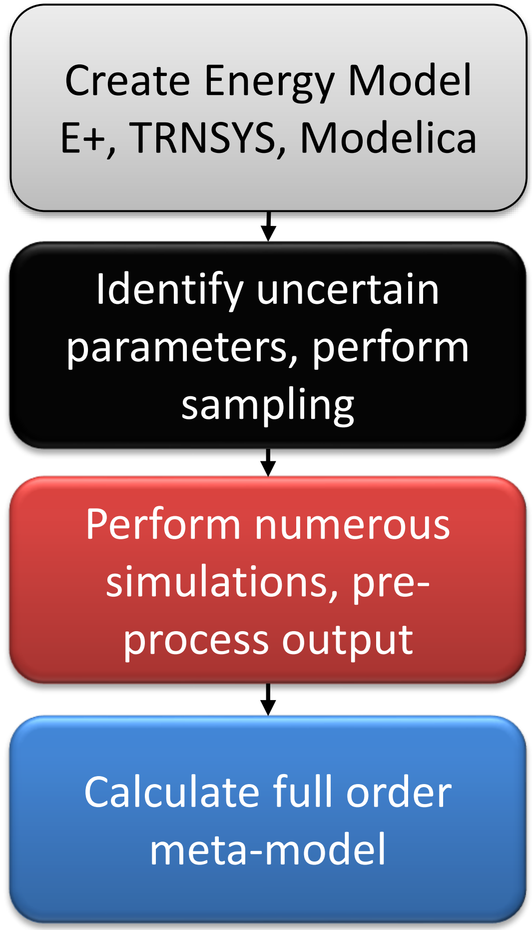


Hand calibration from SA



[E+ Drill Hall]

Zheng O'Neill, Bryan Eisenhower, et al
Modeling and Calibration of Energy Models for a DoD Building ASHRAE Annual Conference, Montreal 2011

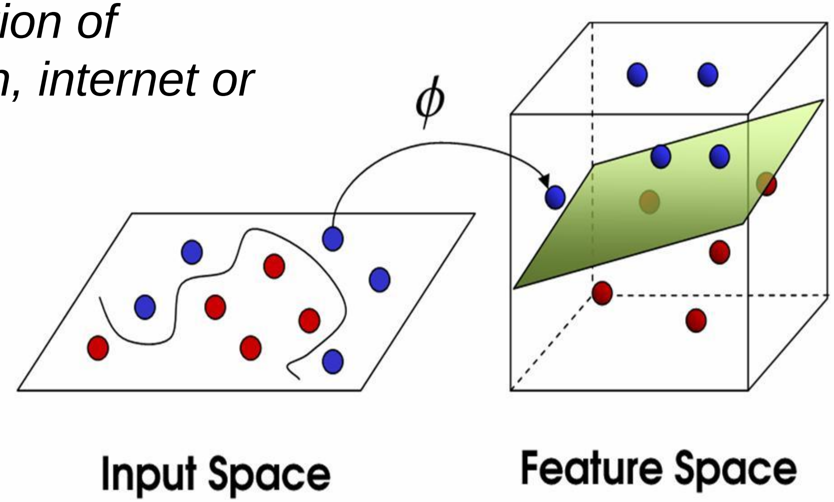

Create Energy Model
E+, TRNSYS, Modelica
Identify uncertain parameters, perform sampling
Perform numerous simulations, pre-process output
Calculate full order meta-model

Machine Learning / Regression

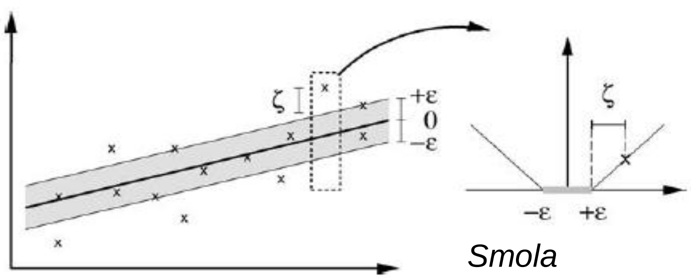
UC SANTA BARBARA engineering

- ❑ 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….

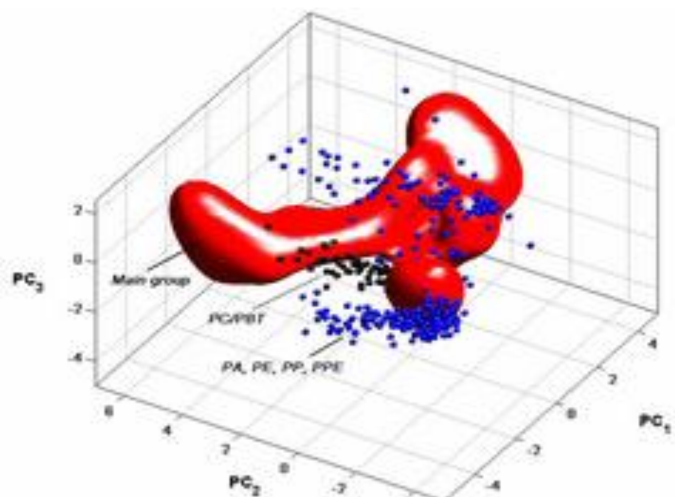
Principle of Support Vector Machines (SVM)



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



Smola [2004]



http://www.da-sol.com/en/resources/starter-pages/svm-starter/

Machine learner

Credit: Ben Hider/Getty Images

Meta-modeling - Results

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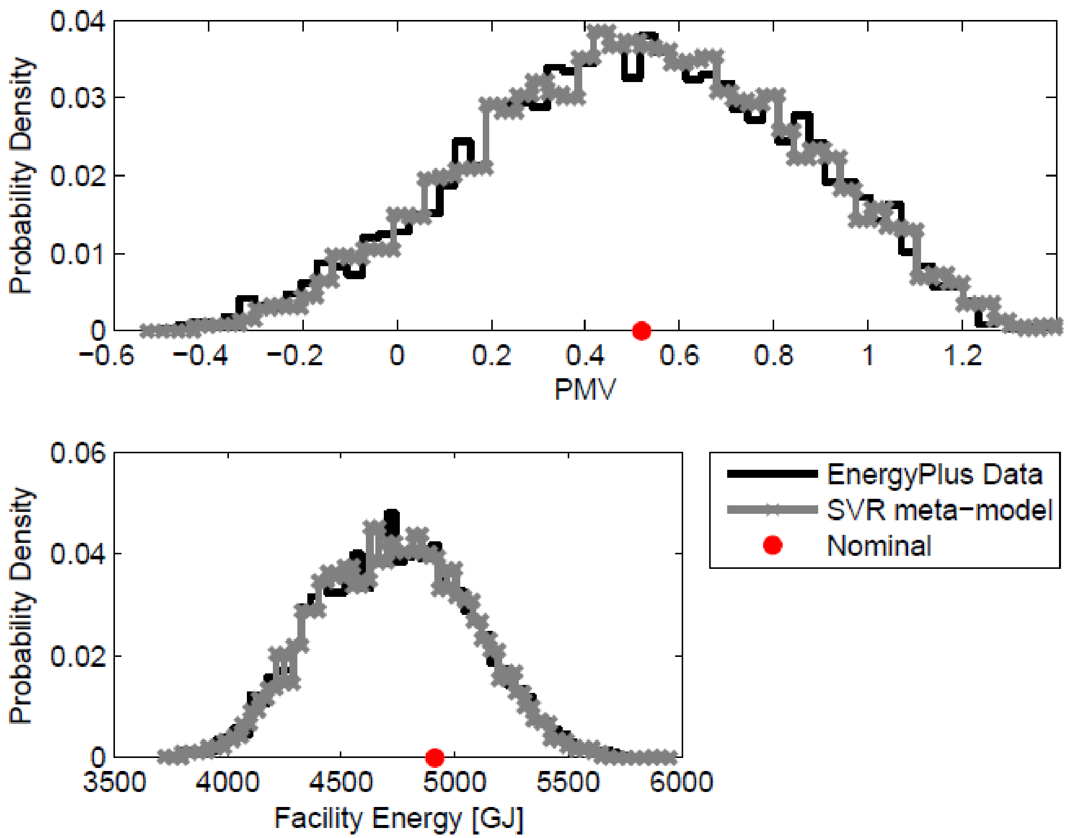
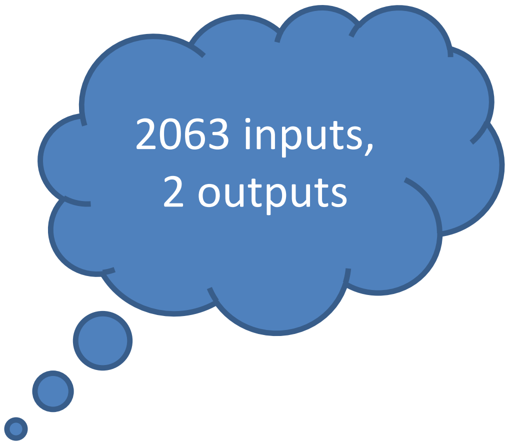
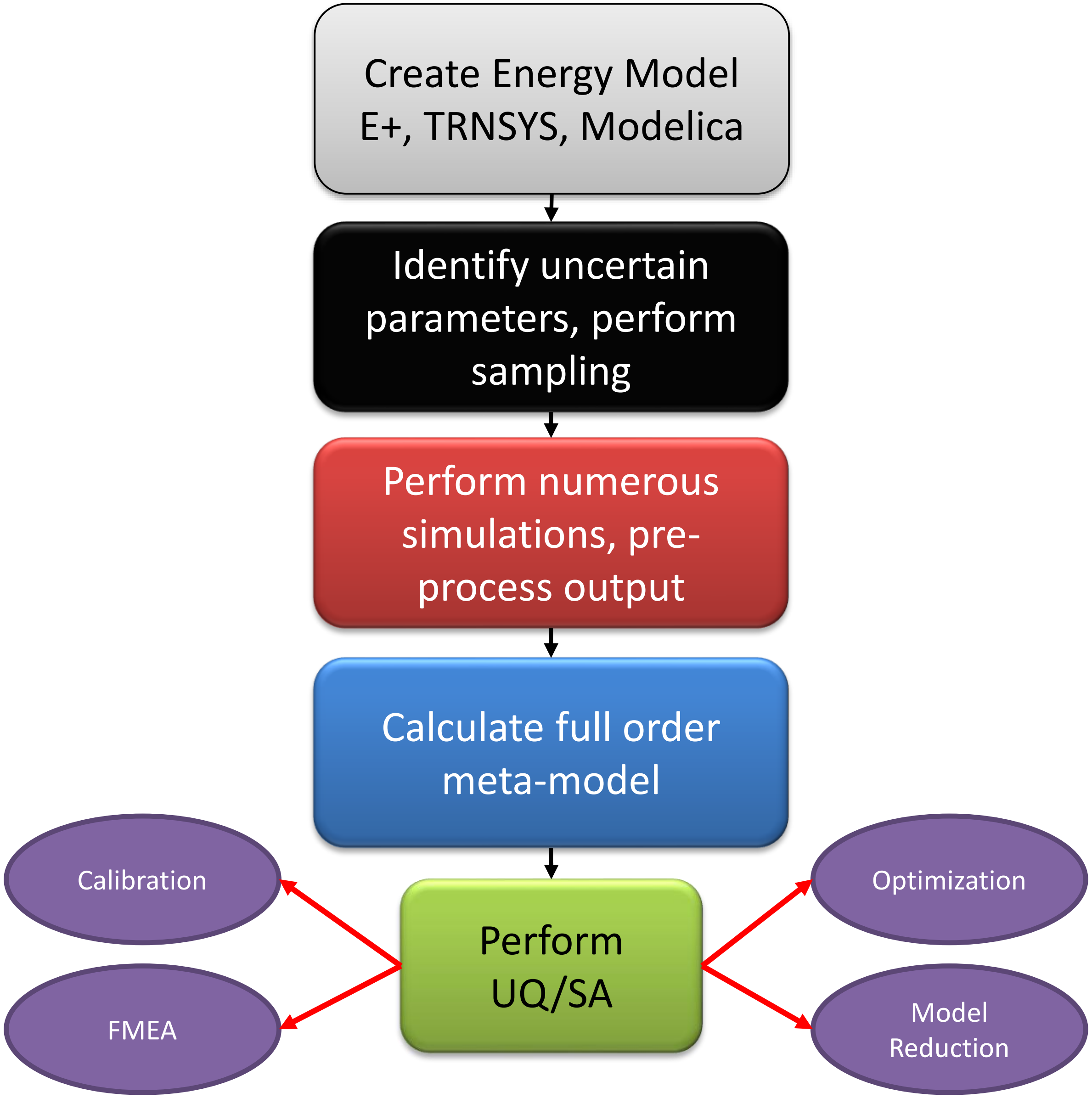
- ❑ A *model of a model* (meta-model) is created to provide means for analytic assessment of building energy & comfort predictions
- ❑ Structure of the model is similar to the full order energy model, *not a line fit to the data*.



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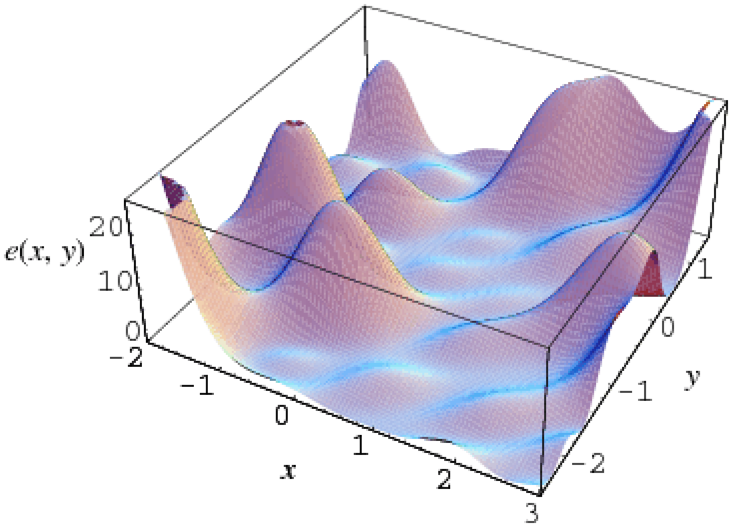
Perform UQ/SA
Calibration
FMEA
Optimization
Model Reduction

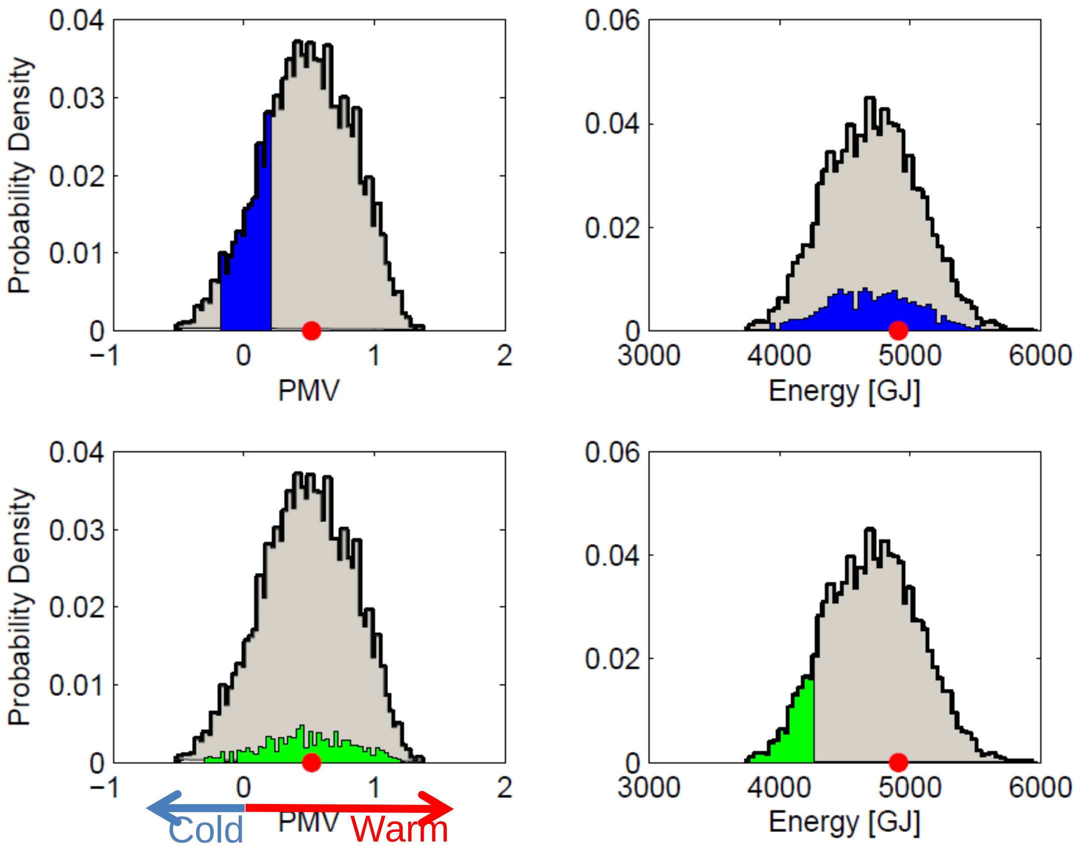


Optimization

$$
\begin{aligned}
&\underset{x}{Min} \quad F(x, Y, Y') \\
&\text{Subject to:} \\
&g_i(x) = 0 \quad i = 1,..,m \\
&h_j(x) \leq 0 \quad j = 1,..,n
\end{aligned}
$$

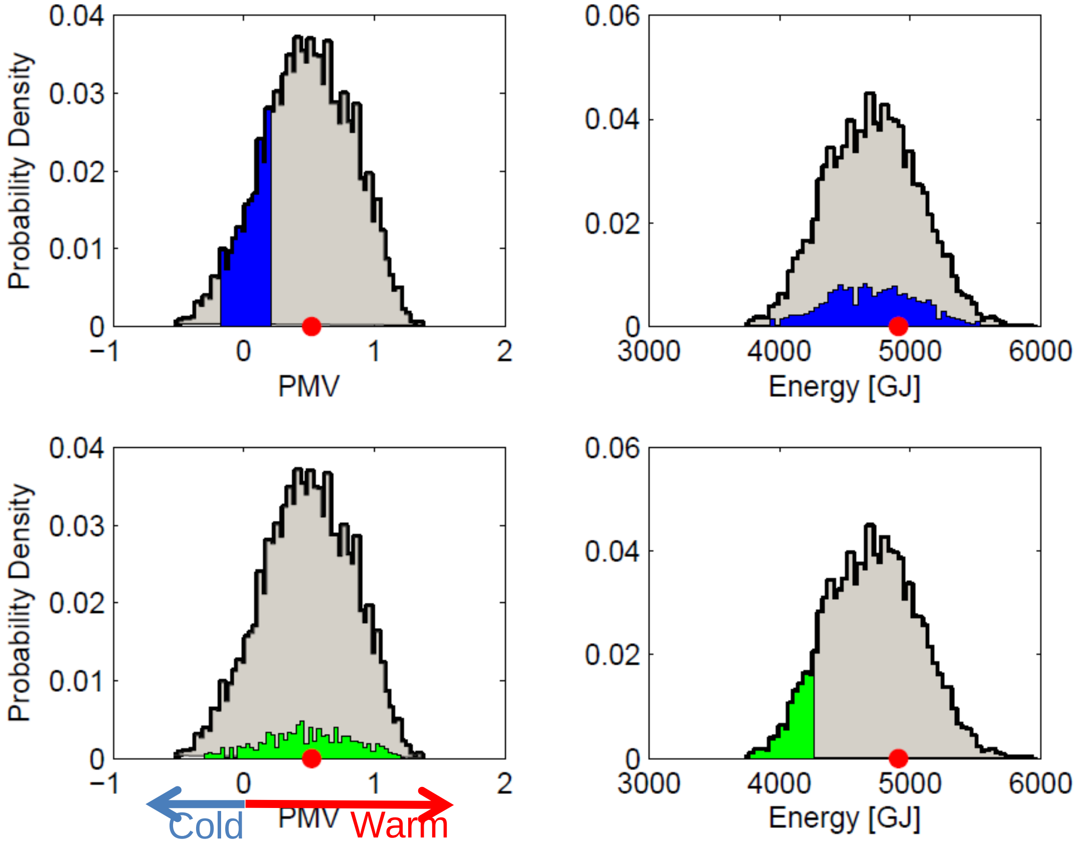
Multi-objective Optimization

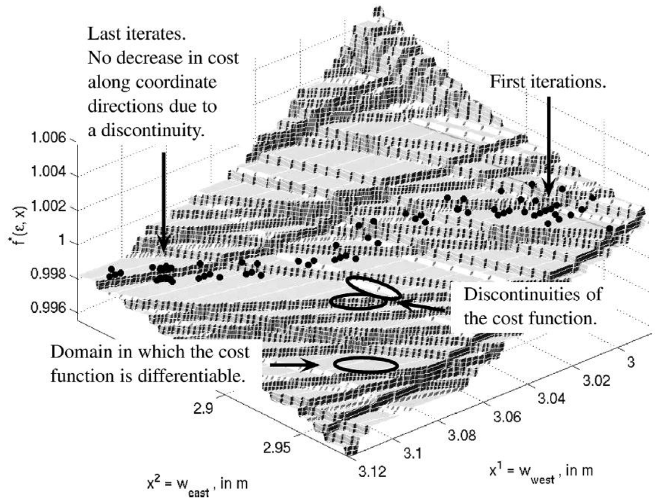
- Objectives in buildings are naturally competitive



Multi-objective Optimization

- ❑ Objectives in buildings are naturally competitive
- ❑ Many whole-building energy simulators do not lend themselves well to optimization

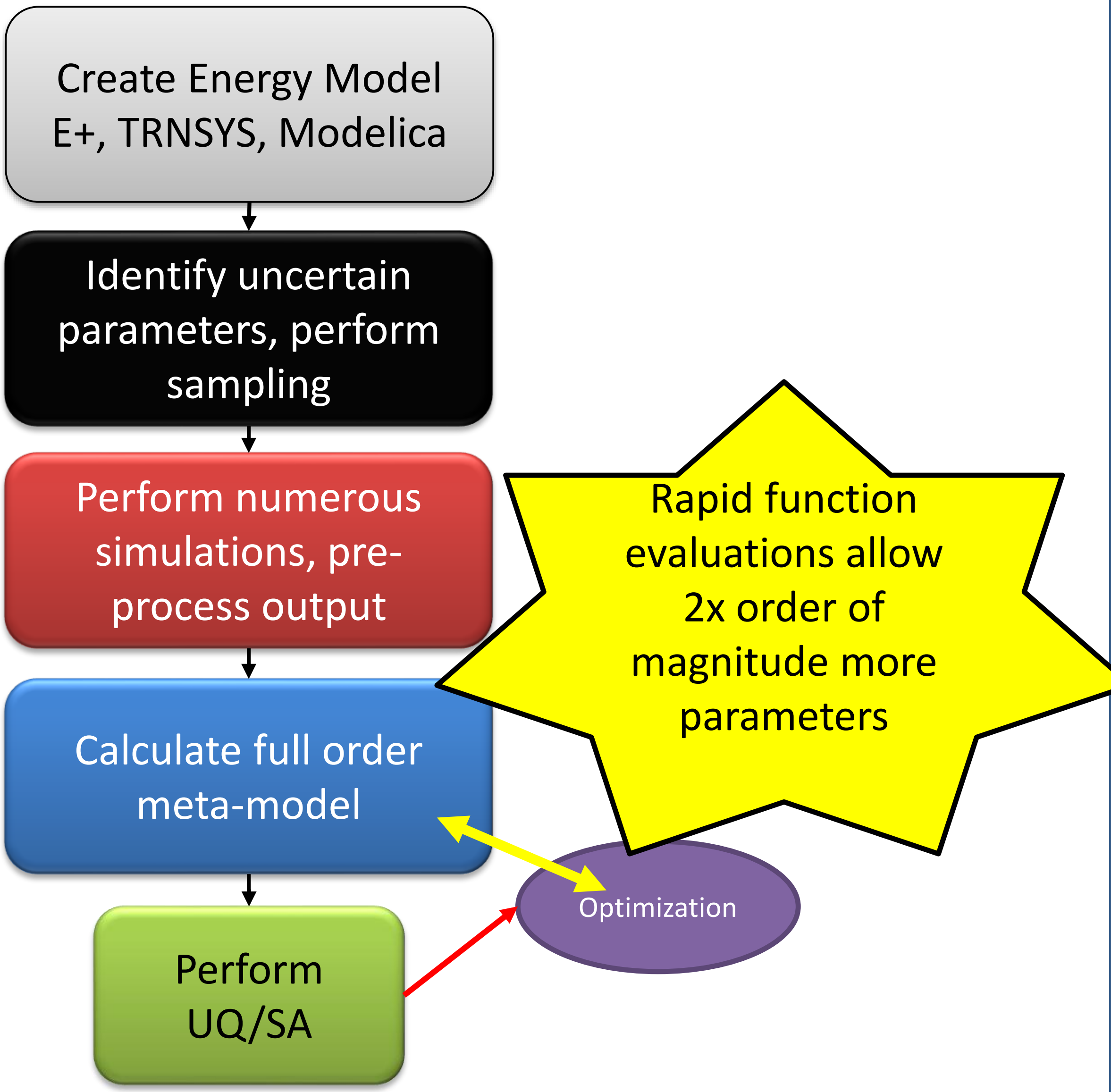




Wetter & Polak 2004

Function evaluations take a long time

Evaluations may get stuck at local minima


Create Energy Model
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Identify uncertain parameters, perform sampling
Perform numerous simulations, pre-process output
Calculate full order meta-model
Perform UQ/SA
Optimization
Rapid function evaluations allow 2x order of magnitude more parameters

Optimization Results

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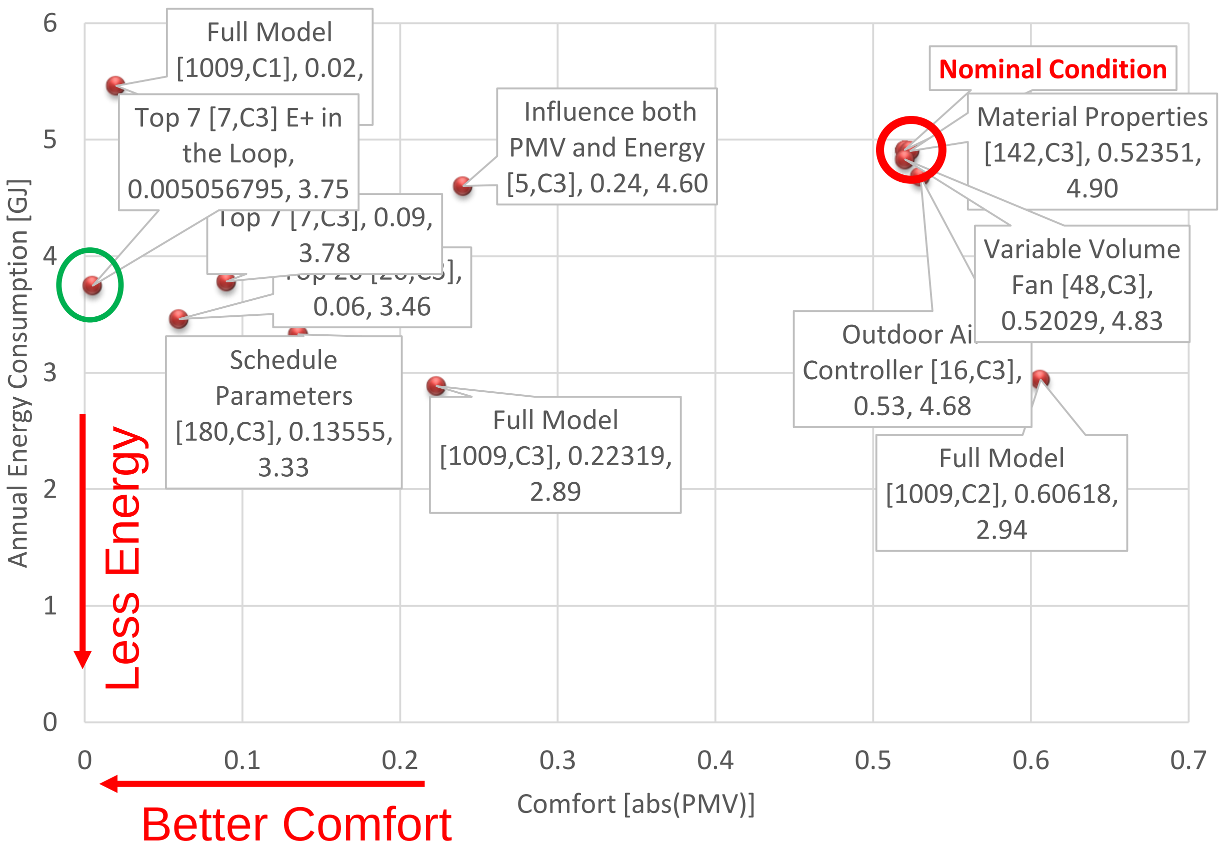
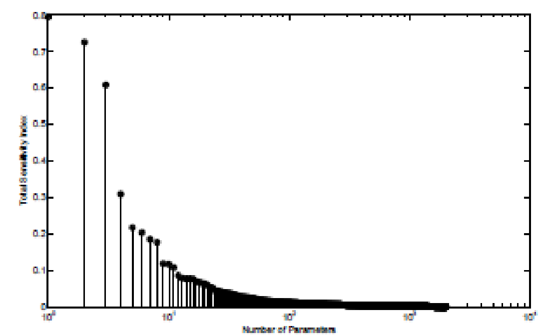
45% annual energy reduction while increasing comfort by a factor of two

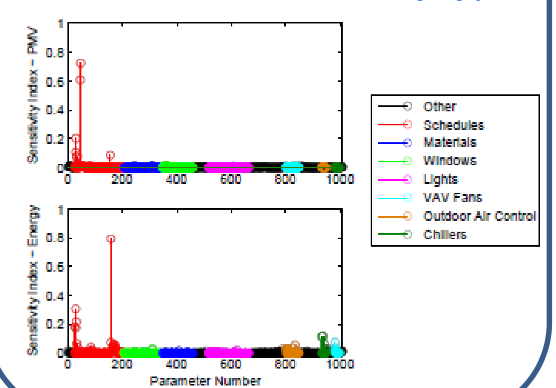


Model reduction based on parameter type or parameter influence

Rank ordering of parameter sensitivity



Parameters collected by type



B. Eisenhower, et al Metamodel-based Optimization of Building Energy Systems *Energy and Buildings 2012*

Model Calibration

Calibration Results

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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 $\sqrt{\sum(\text{model - data})^2}$

Per month, year, etc.

Rank order critical parameters → Assimilate model using output constraints

Calibration Results

Calibration approach tested on DOD Building 26

Data available 2009, 2010, some 2011:

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- Total electricity
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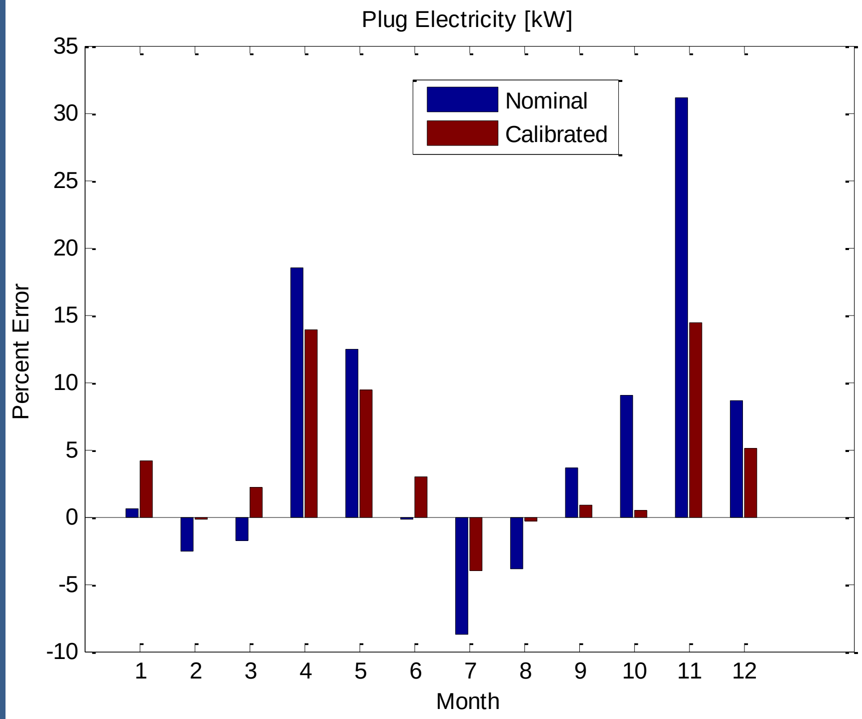

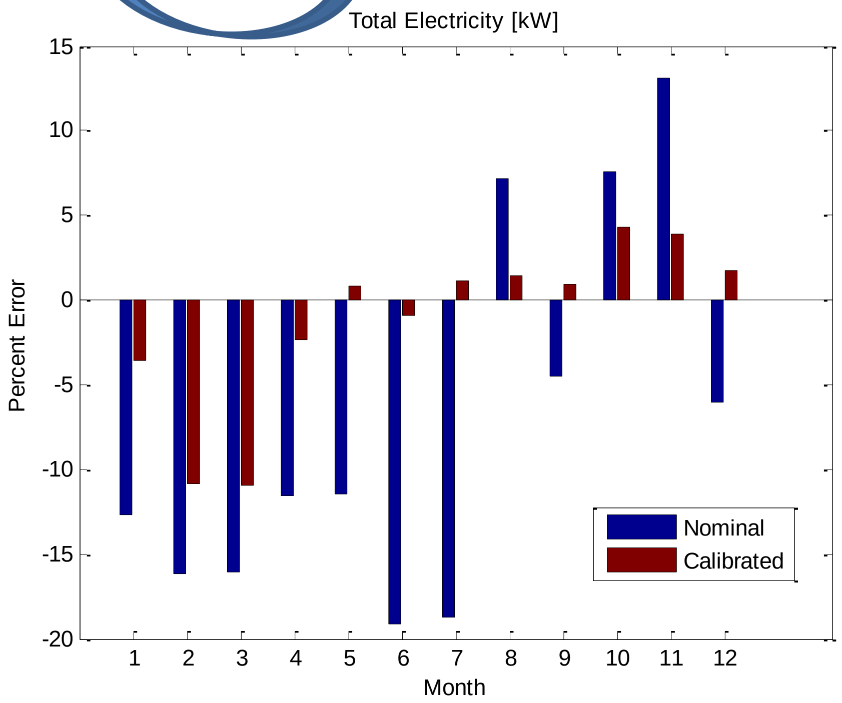

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model-based

Failure Mode Effect Analysis

Modeling Failures

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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

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

*This table from Kevin Otto – RSS (see session 9a SIMBUILD 2012)

Modeling Failures

<u>Partial list of types of Failures</u>

- Sensor error
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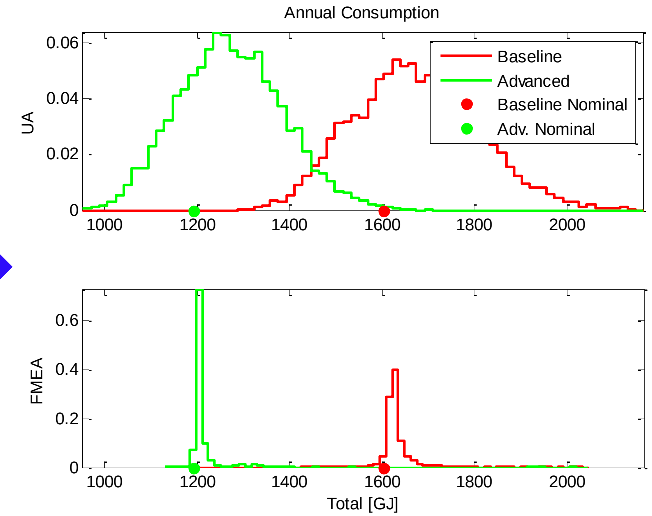
UQ →



Distribution of Failure Modes

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Alarm	Can not Model	Modeled	Total
0%	0%	6%	6%
1%	1%	8%	11%
3%	18%	57%	78%
0%	0%	0%	0%
0%	0%	4%	4%
4%	20%	76%	100%

*This table from Kevin Otto - RSS

FMEA results

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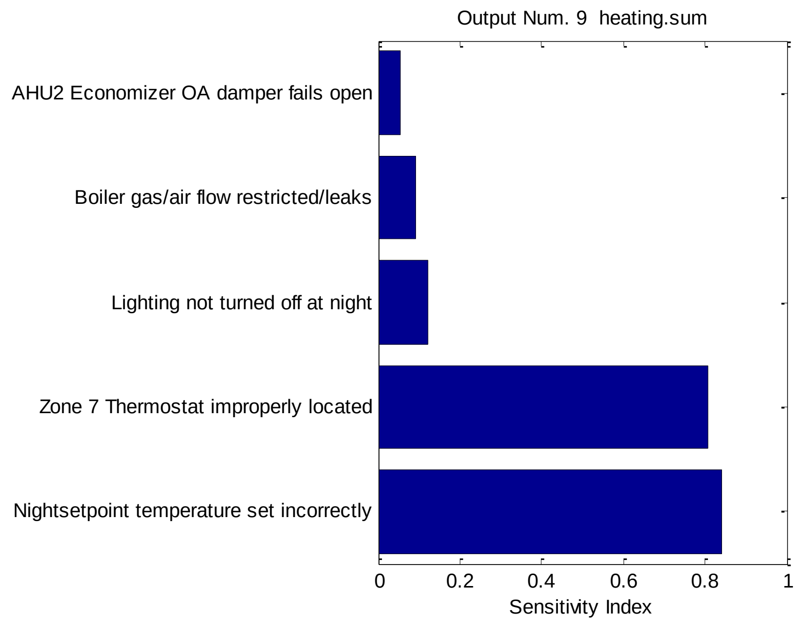
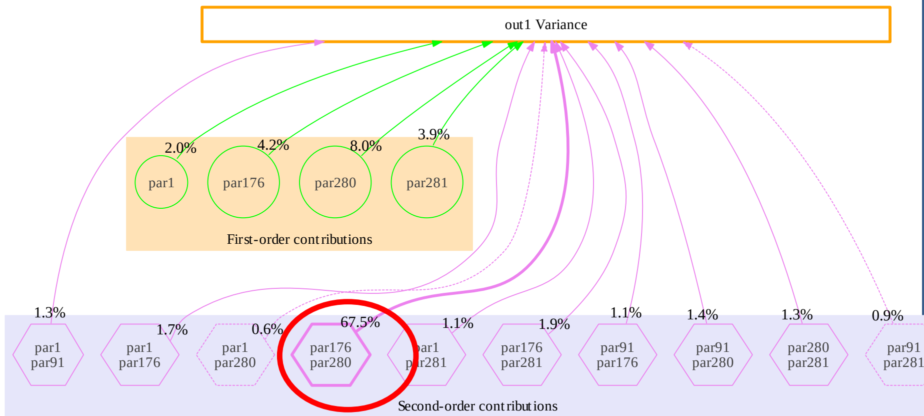
- ❑ Uncertainty analysis illustrates impact of multiple failures on building performance

- ❑ Sensitivity analysis rank orders failures based on their impact



Output 9: Heating Annual Consumption					
	Boiler gas/air flow restricted/leaks	AHU2 Economizer OA damper fails open	Zone 7 Thermostat improperly located	Nightsetpoint temperature set incorrectly	Lighting not turned off at night
Total Sensitivity	0.09	0.05	0.81	0.84	0.12
First Order	0.02		0.04	0.08	0.04
Boiler gas/air flow restricted/leaks		0.01	0.02	0.01	0.01
AHU2 Economizer OA damper fails open			0.01	0.01	0.01
Zone 7 Thermostat improperly located				0.67	0.02
Nightsetpoint temperature set incorrectly					0.01
Lighting not turned off at night					

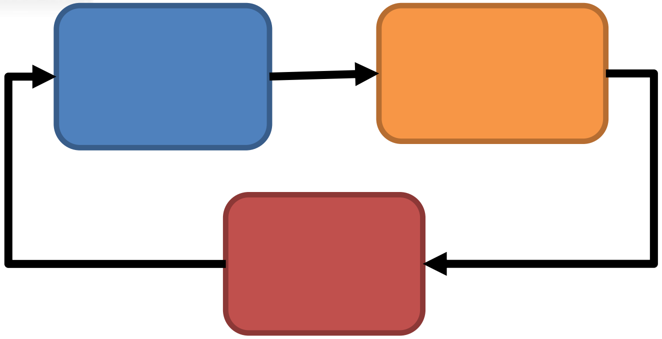


K. Otto, B. Eisenhower, et al. Prioritizing Building System Energy Failure Modes Using Whole Building Energy Simulation SimBuild 2012

- Modeling

- Data

Control



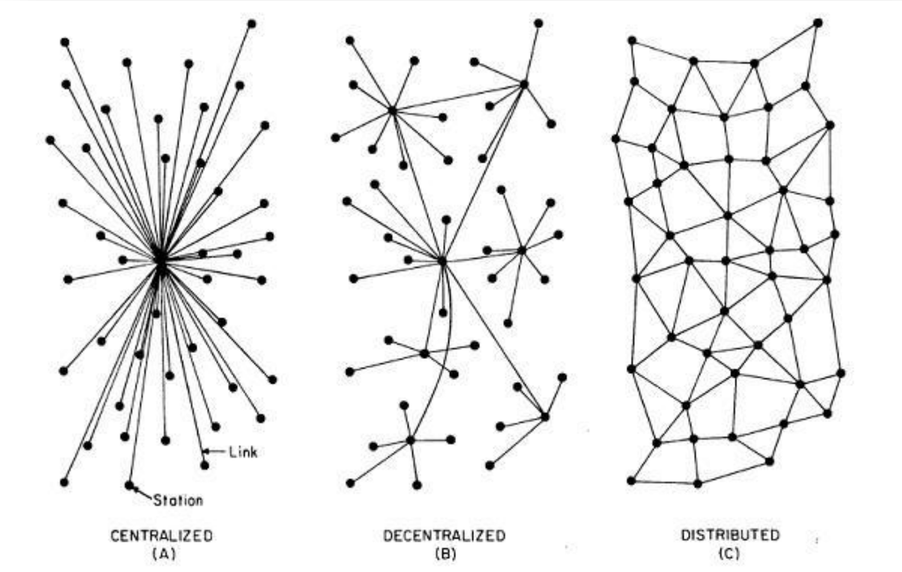
Data Aggregation

Data and control are tied together

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

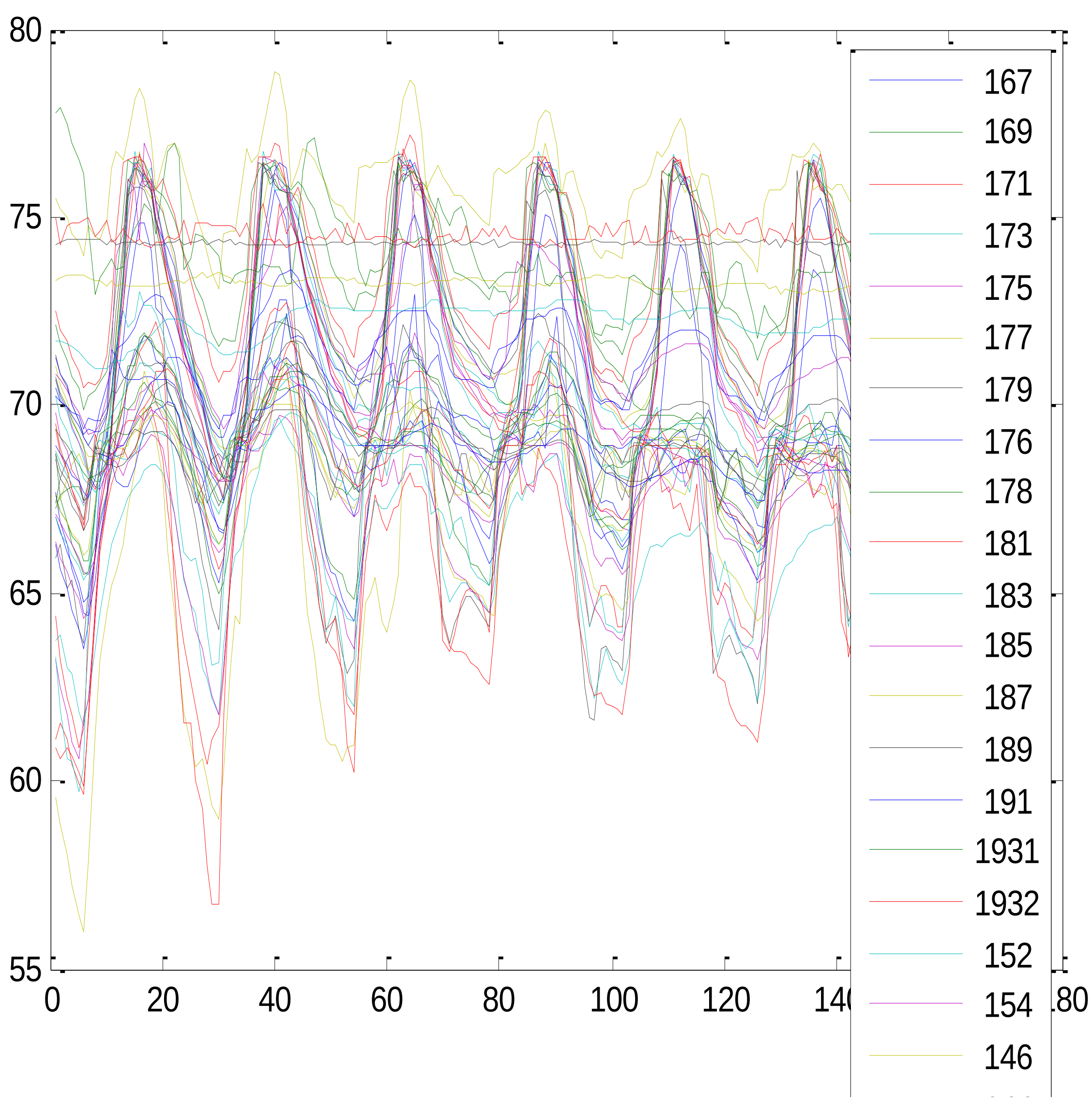
This is robust but causes inefficiencies

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



militantlibertarian.org

Typical Sensor Trends



Typical Sensor Trends

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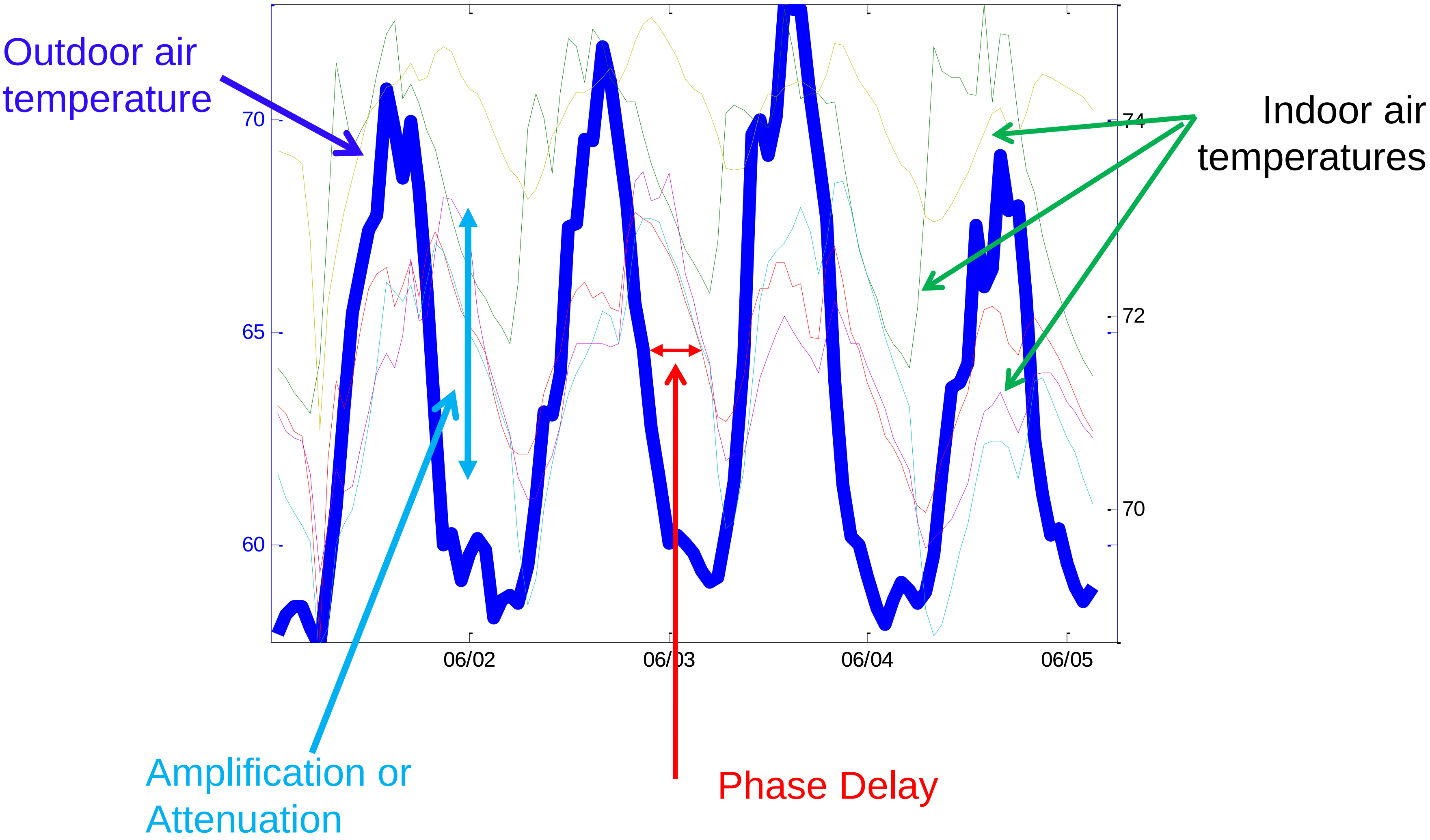
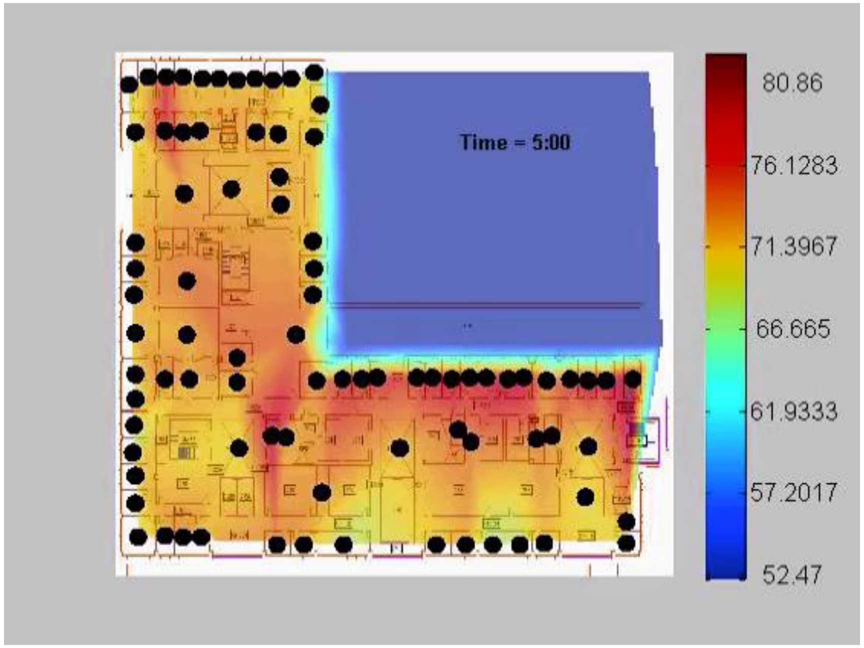


Movies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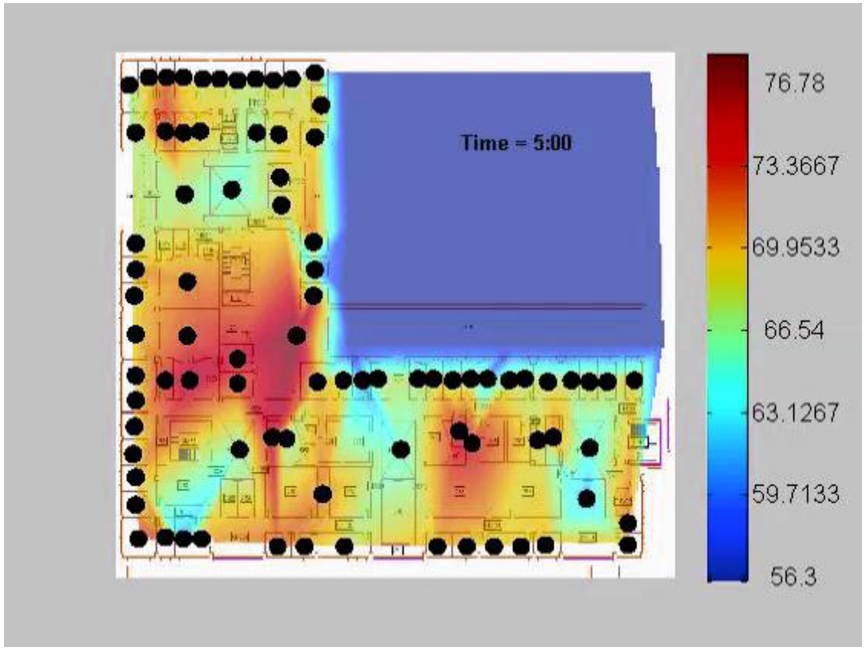
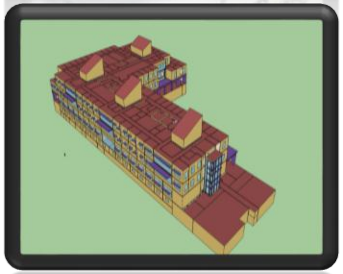
80.86
76.1283
71.3967
66.665
61.9333
57.2017
52.47

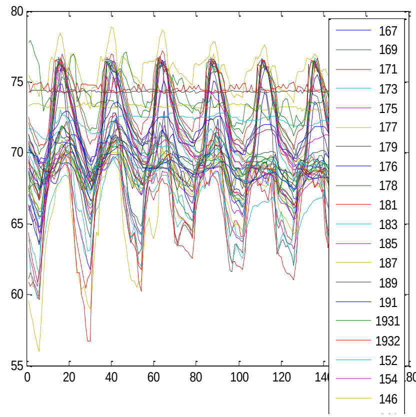

Time = 5:00
76.78
73.3667
69.9533
66.54
63.1267
59.7133
56.3

Spatial-Frequency Analysis



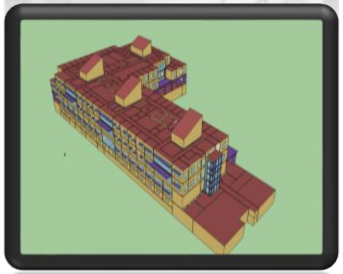
Sensor Information

$\mathcal{O}(1000)$



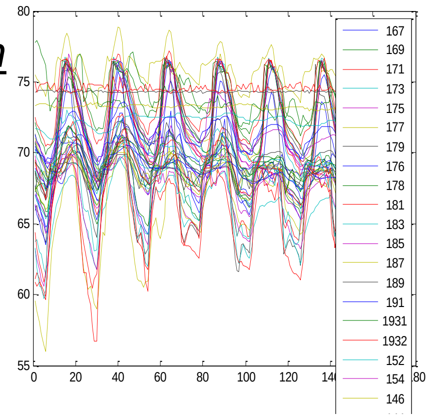
With I. Mezic UCSB

Spatial-Frequency Analysis



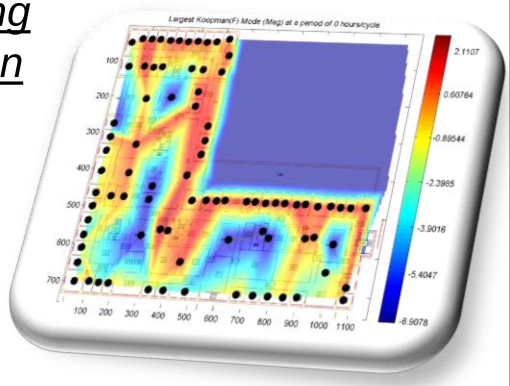
Sensor Information

$\mathcal{O}(1000)$



Engineering Information

$\mathcal{O}(10)$



With I. Mezic UCSB

Spectral Analysis

Spectral Decomposition

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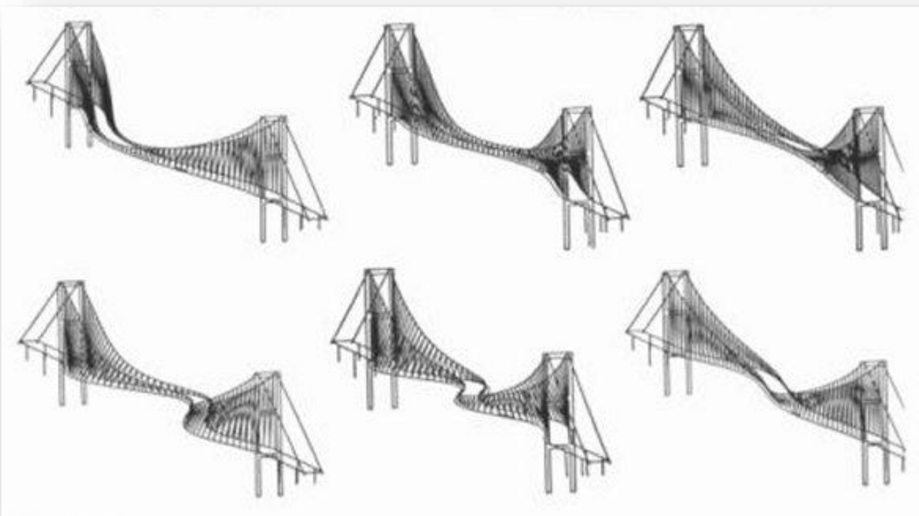
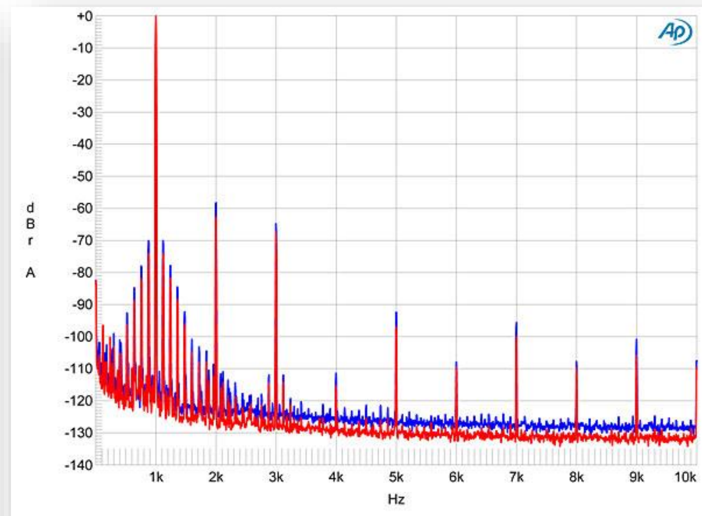
Spectral decomposition is an approach that isolates spatial energy and temporal energy

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



lusas.com

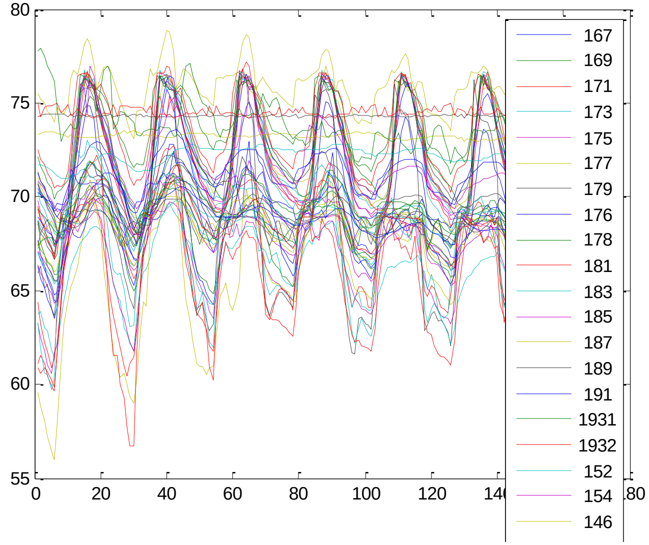


stereophile.com

Space ⟷ Time

Koopman Approach

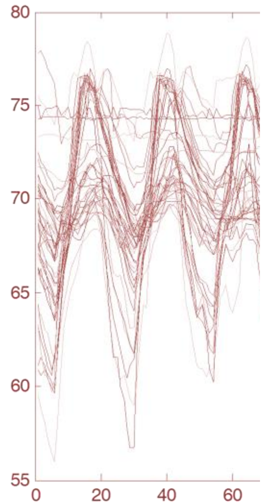
…..Step 1

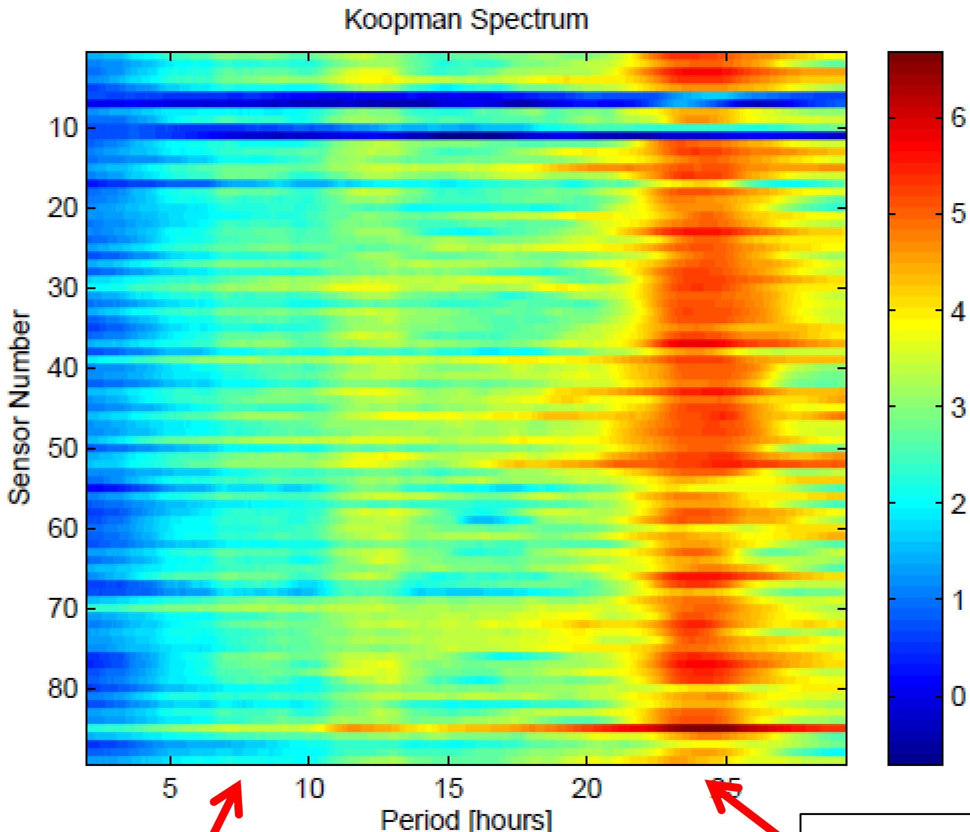


Original and complicated time domain data

Koopman Approach

…..Step 2





Work-day 7-8 hrs

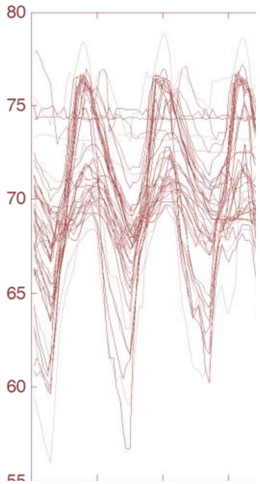
Diurnal

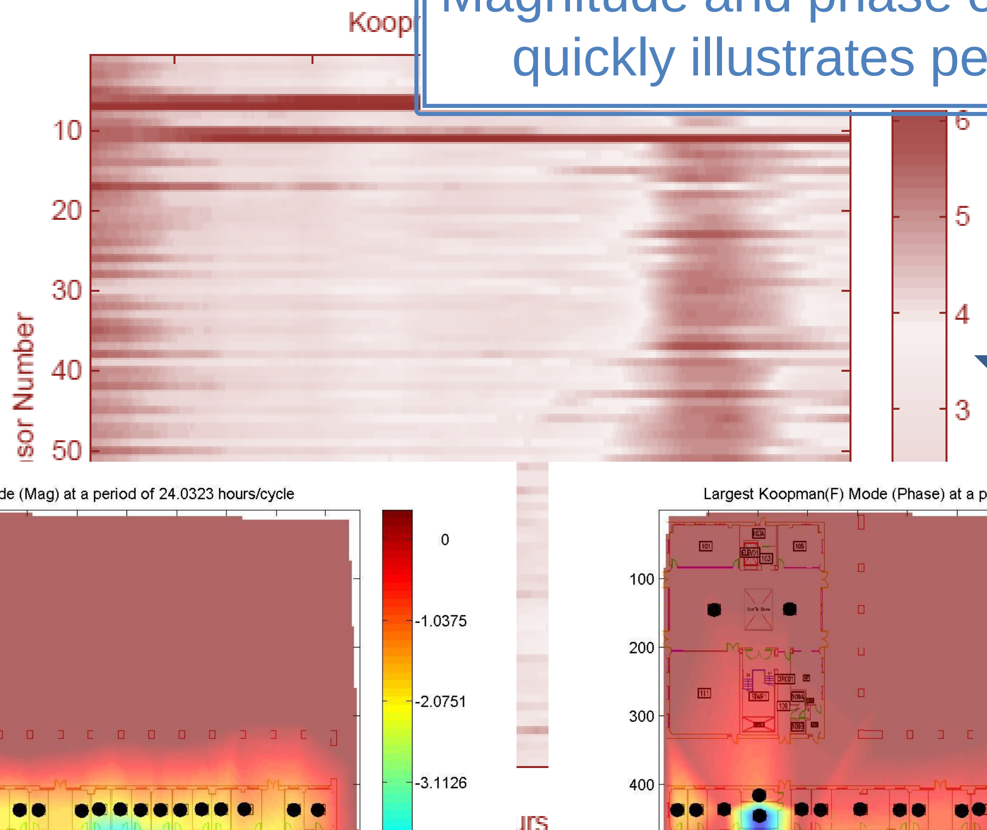
Investigate and choose freq. in Koopman spectrum

Koopman Approach

.....Step 3

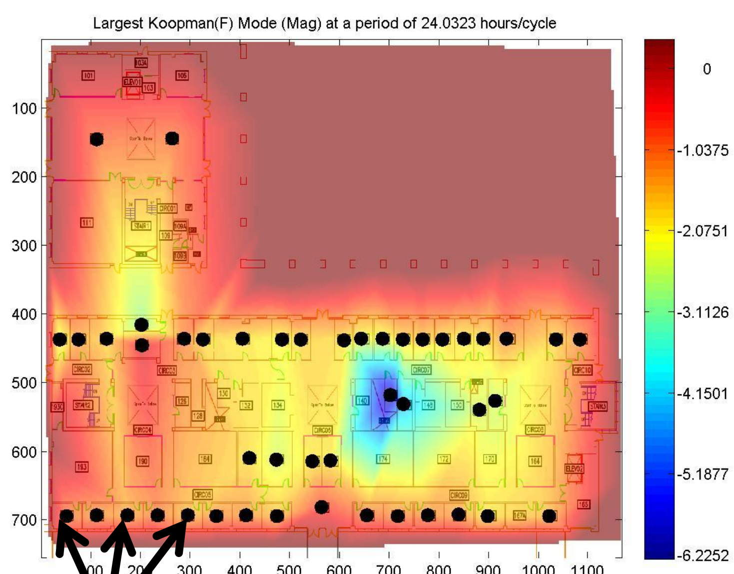
Magnitude and phase of Koopman mode quickly illustrates performance

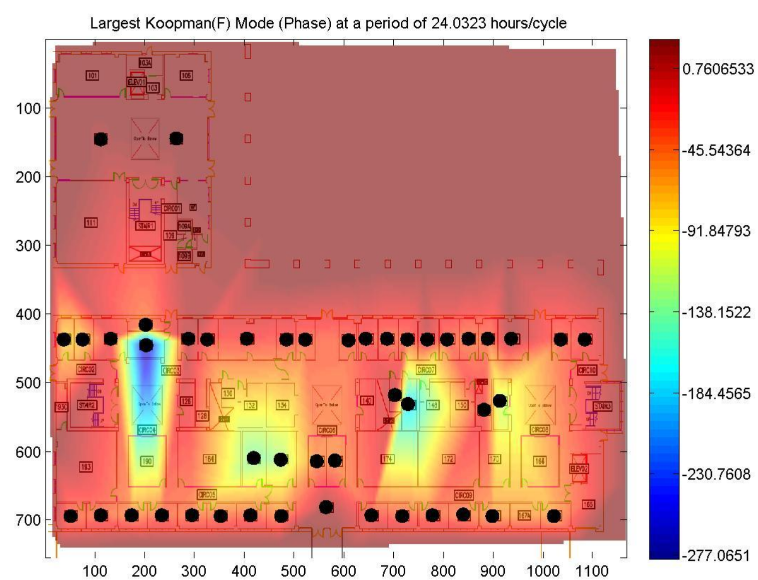




$$|KM(i)| = 20\log_{10}\left|\frac{\Psi_i}{\Psi_{OAT}}\right|$$

$$\angle KM(i) = \angle\Psi_i - \angle\Psi_{OAT}\,.$$





sensors

Architectural floor plan, first floor

Example: Inefficient Control

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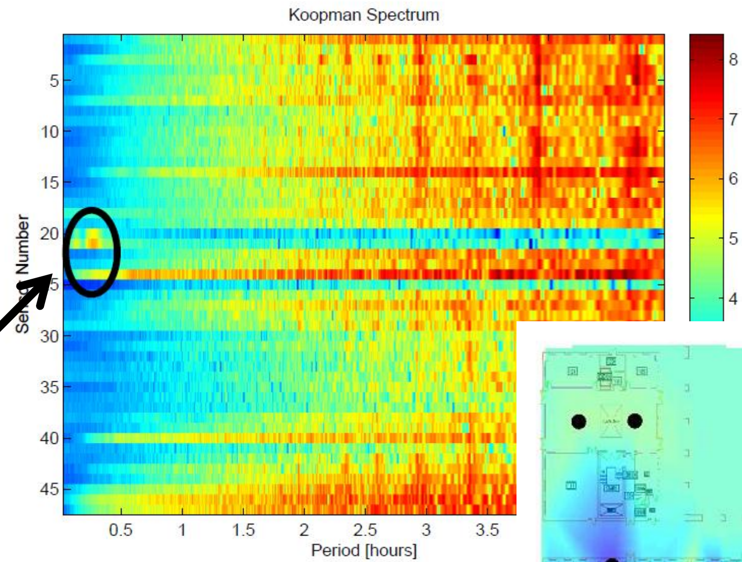
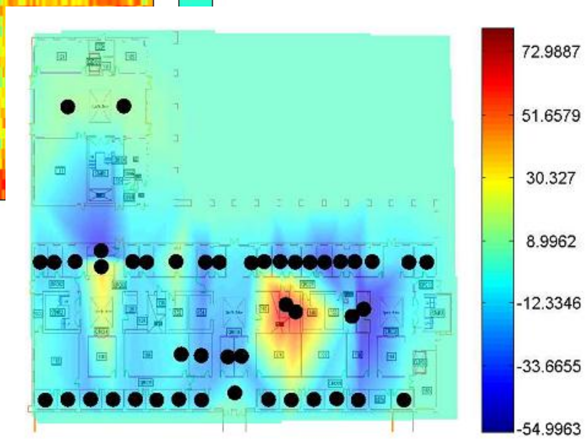
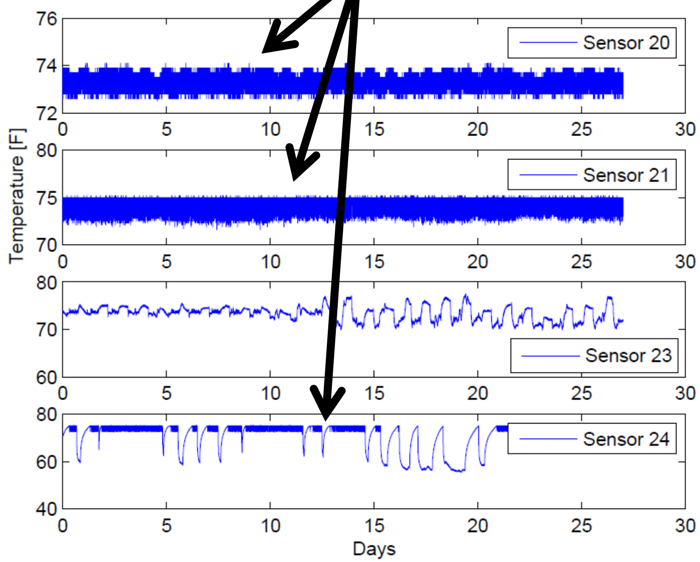
- ❑ Method quickly isolates sensor / control issues

Energy at unexpected frequencies







- ❑ Cycling found in control system
- ❑ System retuned to reduce cycling

Example – Model Tuning

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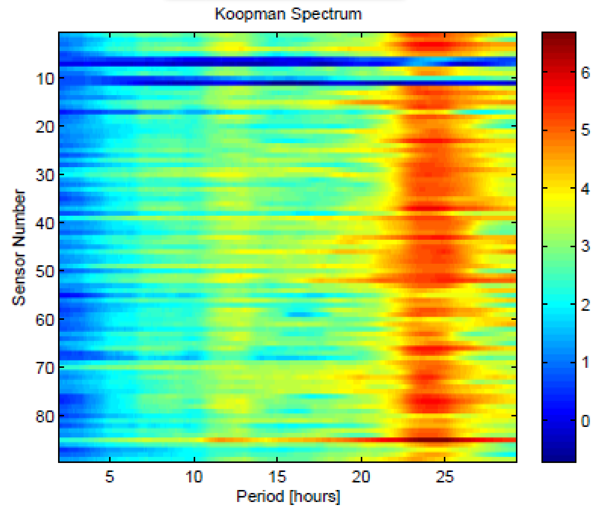
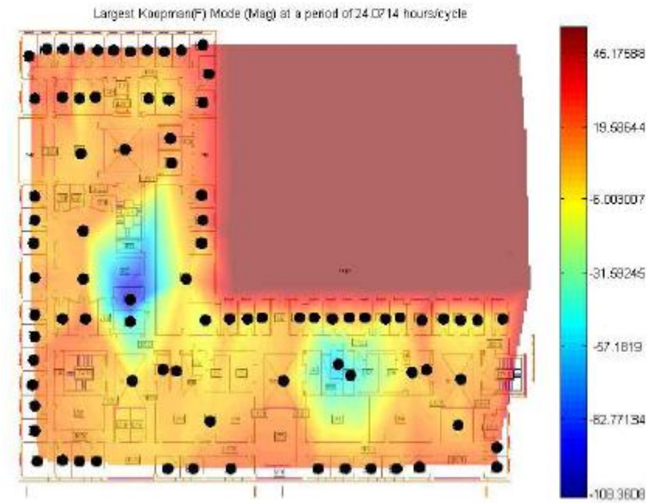
- Comparison between extensive EnergyPlus model and data

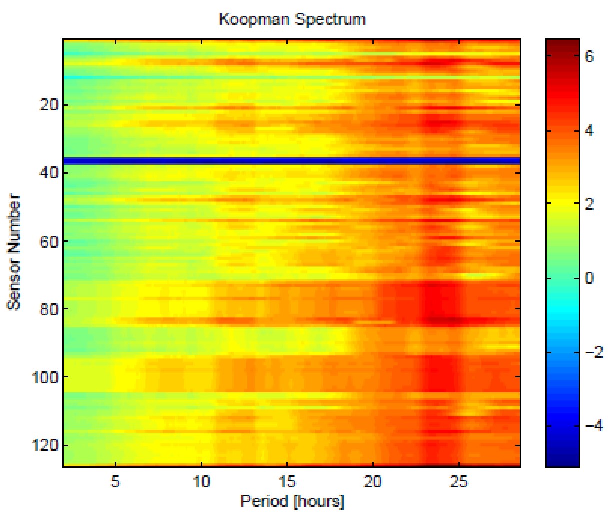
Spectrum | **Magnitude**

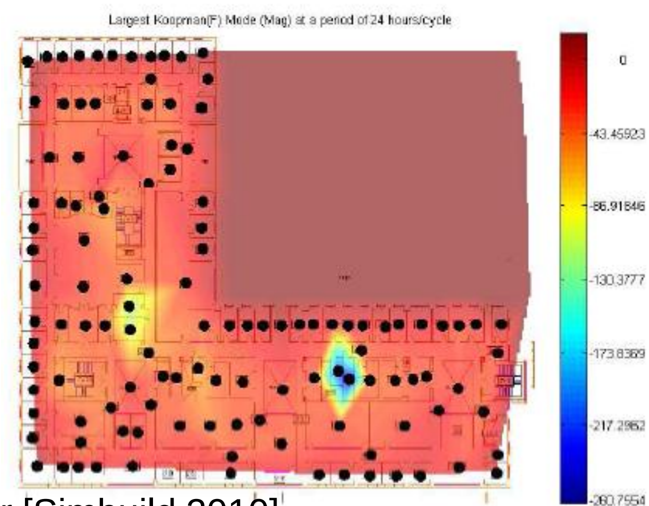
Data





Model





Eisenhower [Simbuild 2010]

Hong Kong: Efficiency analysis*

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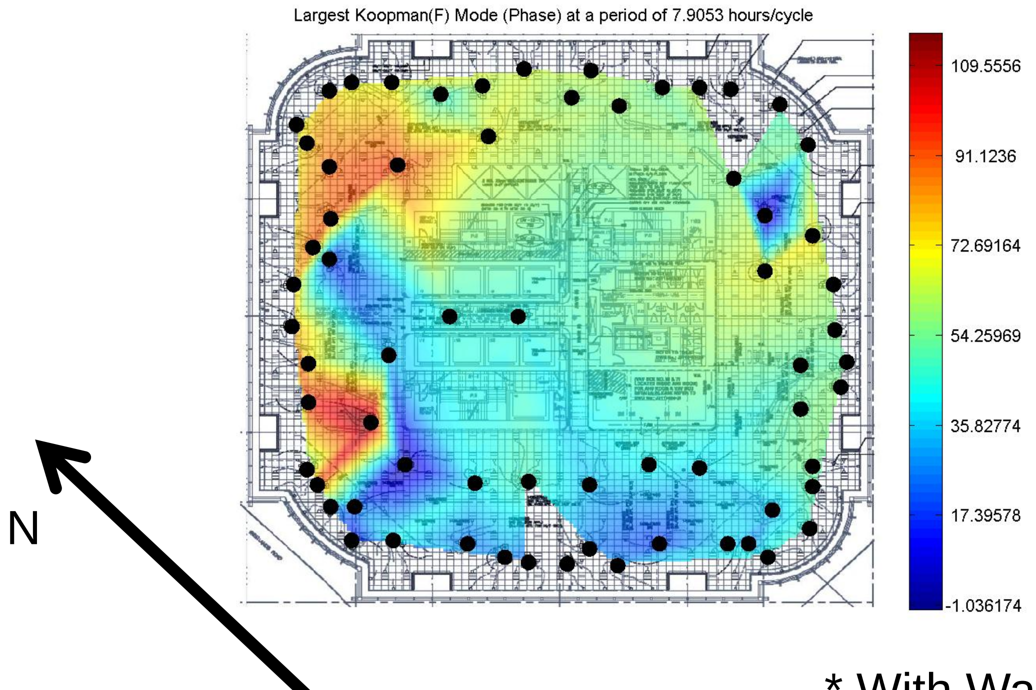
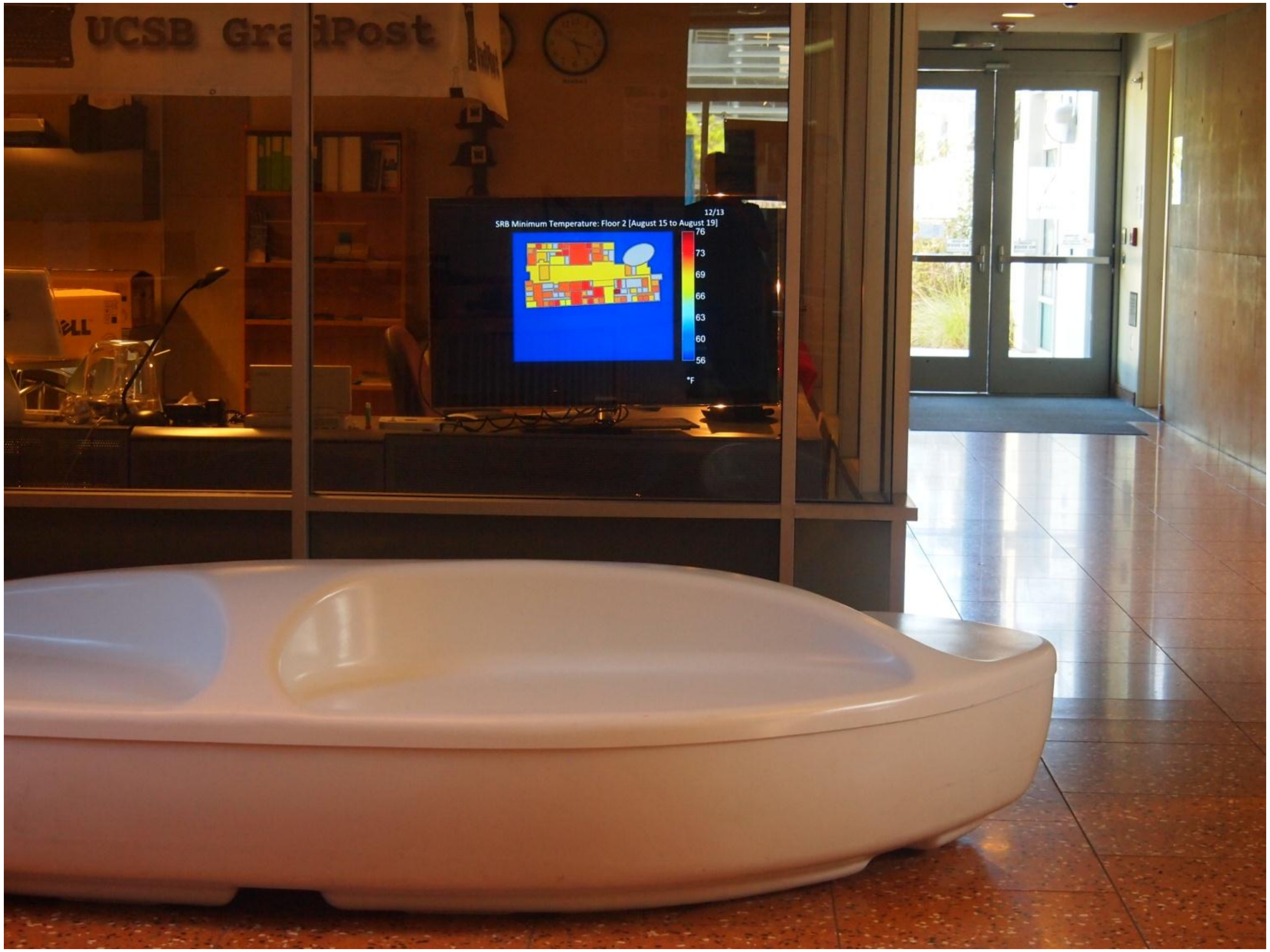
❑ One Island East – Westlands Rd. Hong Kong
- 70 story sky-scraper
- Data: 11/1/2009 – 11/15/2009

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

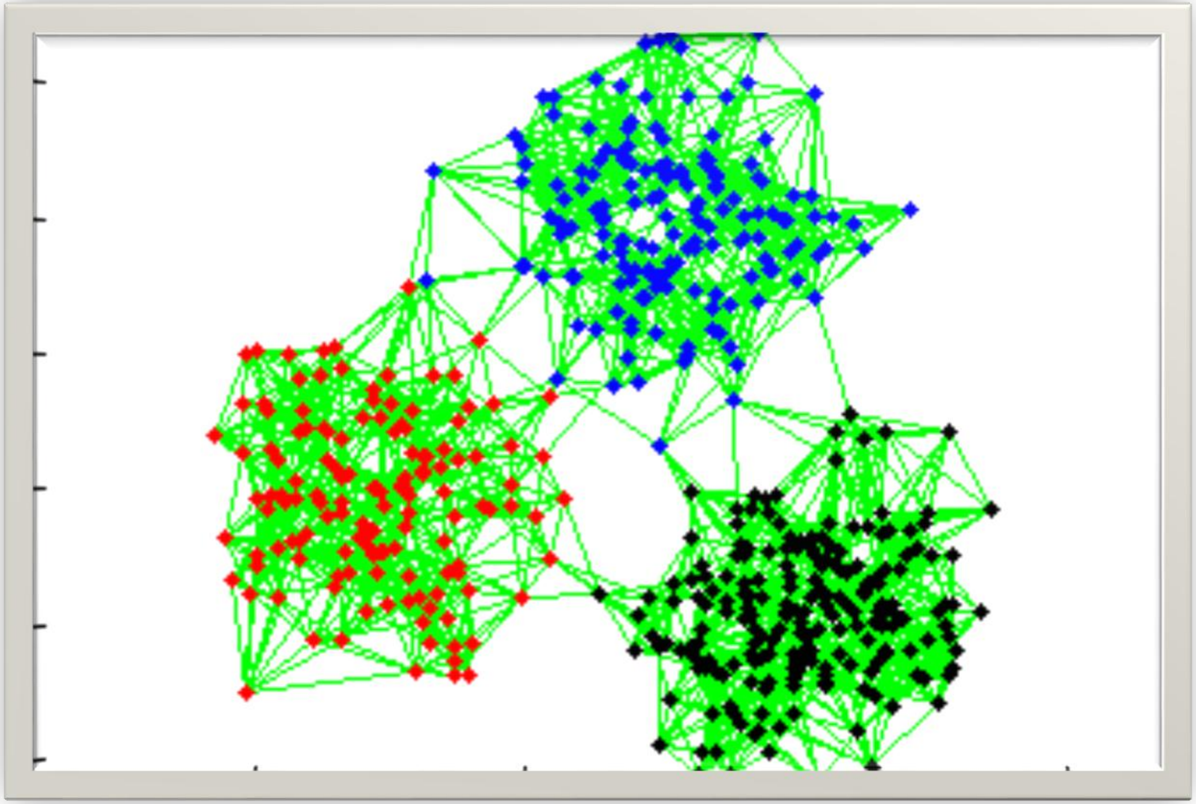


* With Walter Yuen, Hong Kong Poly. Univ.

Installed Monitor @ UCSB



Clustering

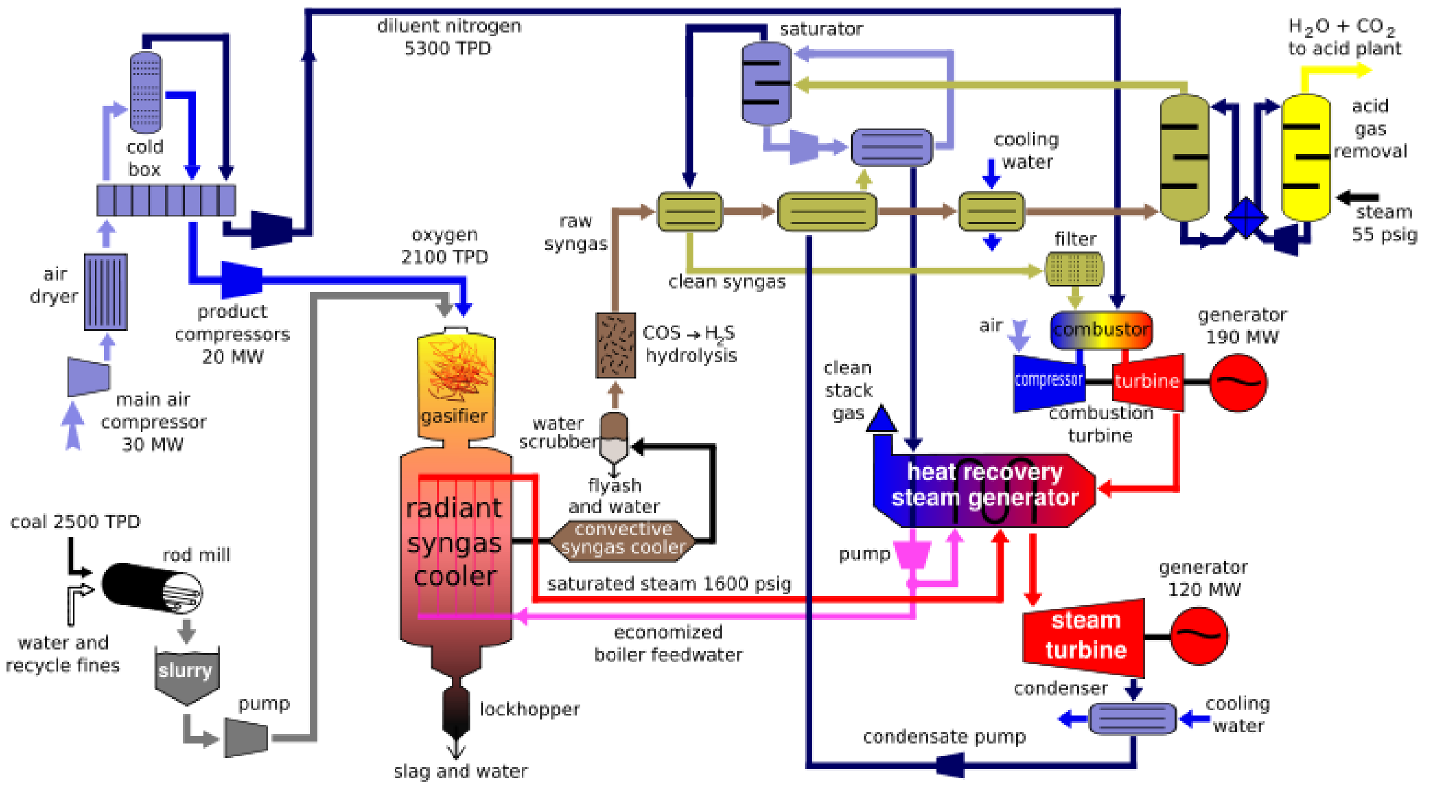


Decomposition Methods

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

<u>Integrated Gasification Combined Cycle, or IGCC, is a technology that turns coal into gas into electricity</u>



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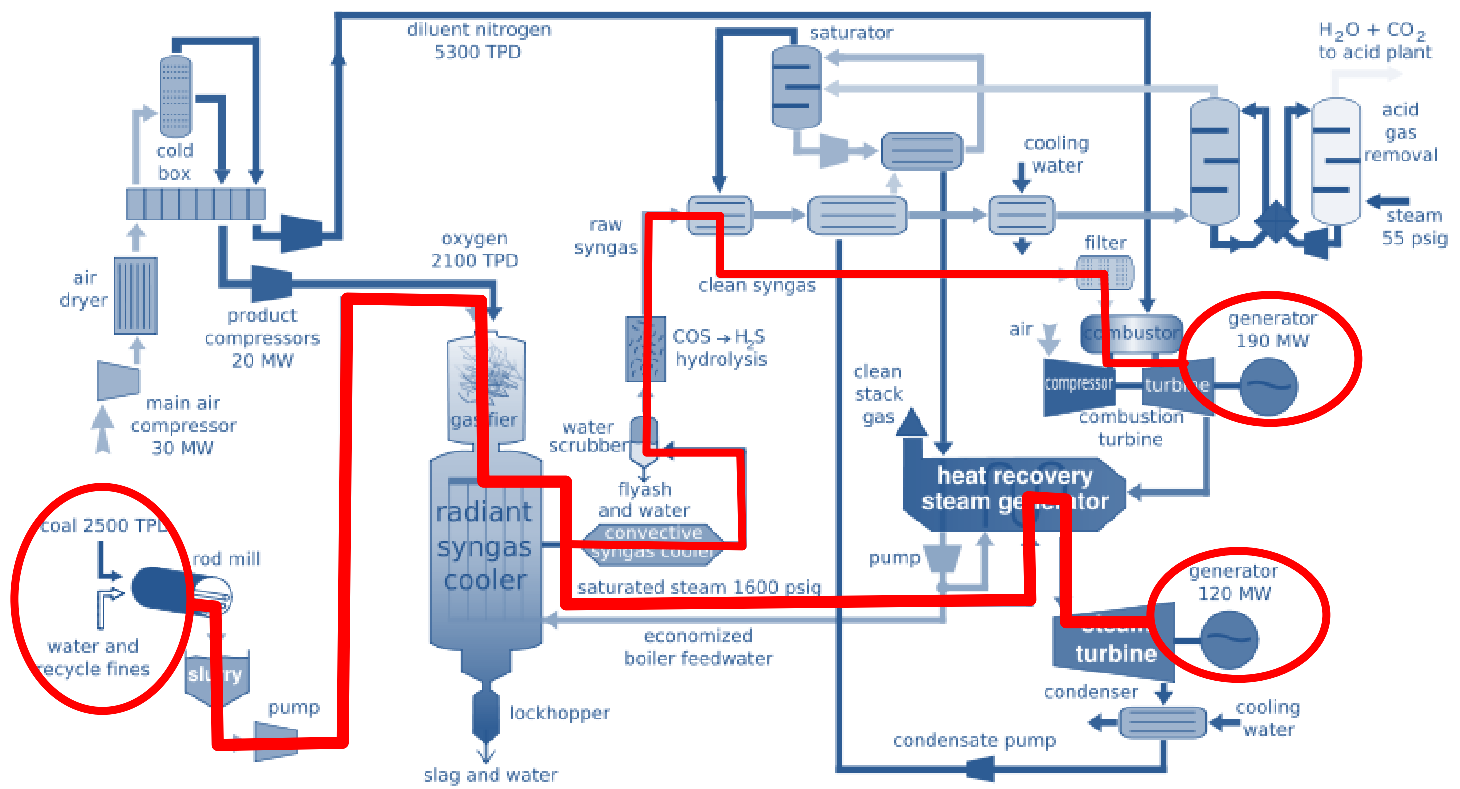
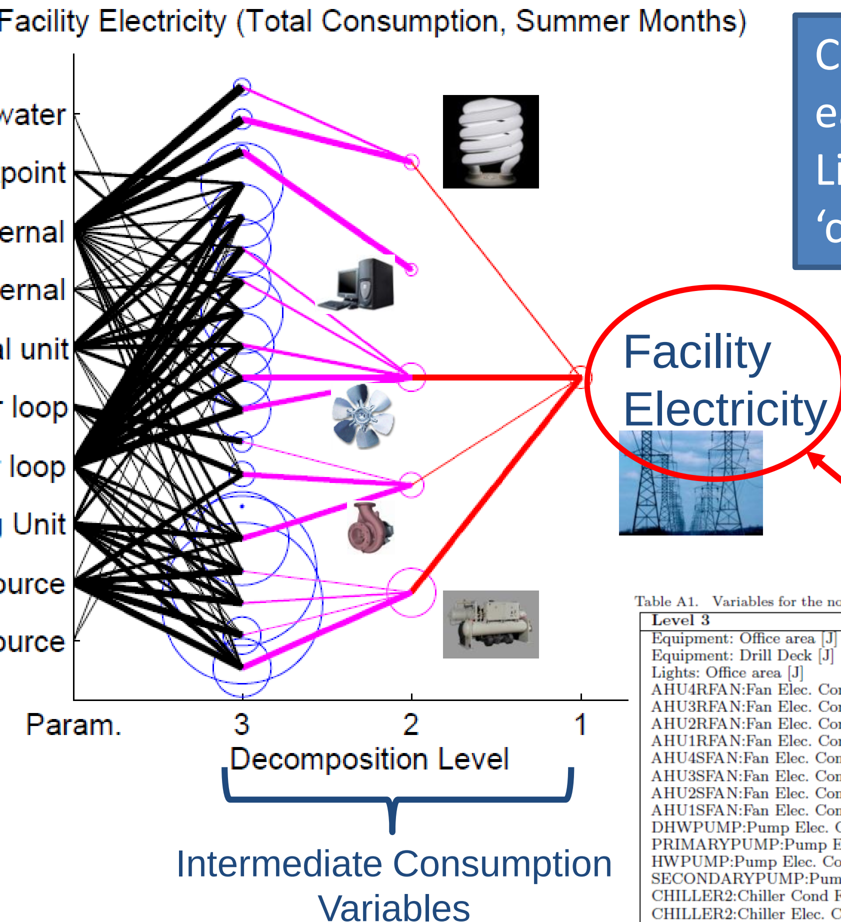


Uncertainty at each node and pathway flow identified for a heterogeneous building



Circles: Uncertainty at each node
Line Thickness: 'conductance'

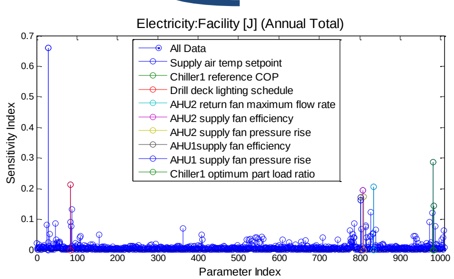
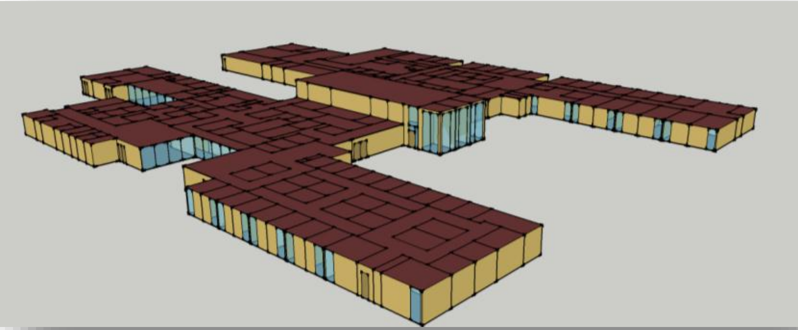


Table A1. Variables for the nodes of the sensitivity decomposition of Facility Electricity (Figure 7).

Level 3	Level 2	Level 1
Equipment: Office area [J]		
Equipment: Drill Deck [J]		
Lights: Office area [J]		
AHU4RFAN:Fan Elec. Cons. [J]		
AHU3RFAN:Fan Elec. Cons. [J]		
AHU2RFAN:Fan Elec. Cons. [J]	InteriorLights:Elec. [J]	
AHU1RFAN:Fan Elec. Cons. [J]		
AHU4SFAN:Fan Elec. Cons. [J]	Int.Equip.:Elec. [J]	
AHU3SFAN:Fan Elec. Cons. [J]		
AHU2SFAN:Fan Elec. Cons. [J]	Fans:Elec. [J]	Facility Elec. [J]
AHU1SFAN:Fan Elec. Cons. [J]		
DHWPUMP:Pump Elec. Cons. [J]	Pumps:Elec. [J]	
PRIMARYPUMP:Pump Elec. Cons. [J]		
HWPUMP:Pump Elec. Cons. [J]	Cooling:Elec. [J]	
SECONDARYPUMP:Pump Elec. Cons. [J]		
CHILLER2:Chiller Cond Fan Elec. Cons. [J]		
CHILLER2:Chiller Elec. Cons. [J]		
CHILLER1:Chiller Cond Fan Elec. Cons. [J]		
CHILLER1:Chiller Elec. Cons. [J]		

Eisenhower et al. Uncertainty and Sensitivity Decomposition of Building Energy Models *Journal of Building Performance Simulation, 2011*

Clustering Dynamics



Detailed Whole-Building Model

Detailed Energy Software

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{surfaces}} \dot{Q}_{conv_i} + \sum_{i=1}^{N_{zones}} \dot{Q}_{mixing_i} + \sum_{i=1}^{N_{sl}} \dot{Q}_{sl_i} + \dot{Q}_{inf_z} + \dot{Q}_{HVAC_z}, \quad (1)$$

$$\dot{x} = A(x_0, p)x + B_u(x_0)u + B_w(x_0, p)w$$
$$y = Cx$$

Analytic Meta-model

Clustering

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Test case:
Medium office building, 53 kft^2, 18 zones

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

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

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

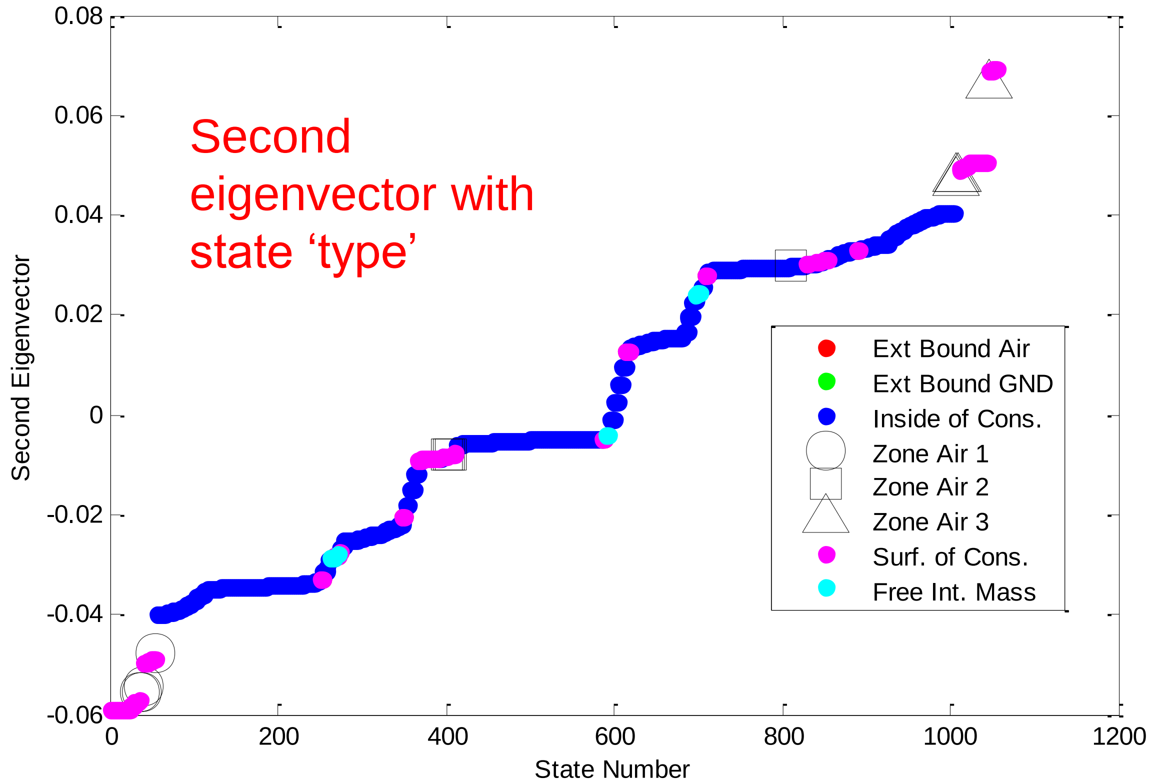
$$L = \deg(W) - W$$

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

T_{zones}(x18)

Internal States (x1056)

$T_{outdoors}$
T_{ground}
$T_{HVACsupply}$
$T_{window\ surface}$



Clustering

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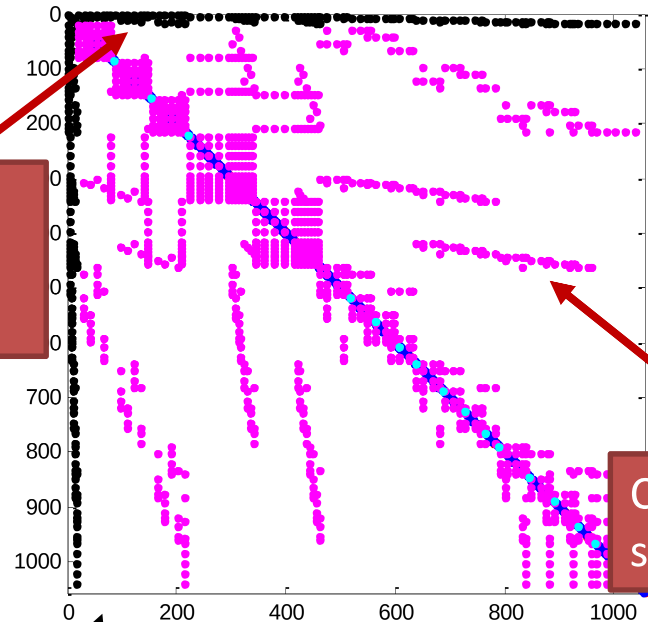
Unsorted *A* matrix interconnections

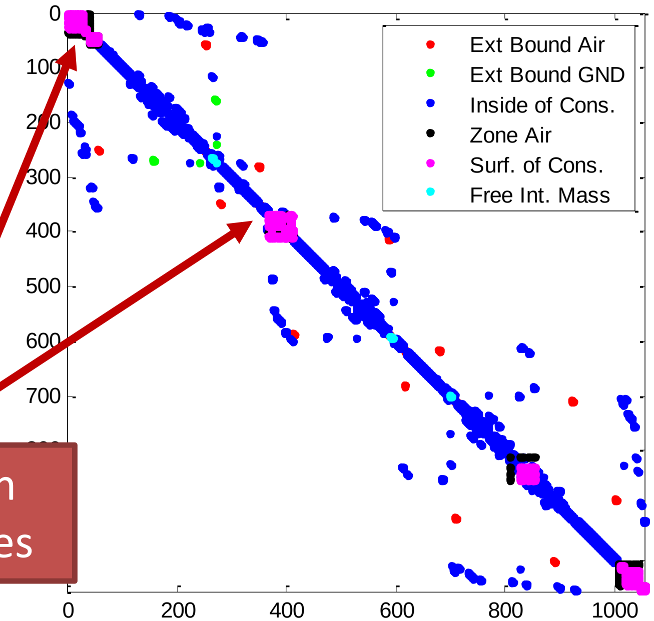


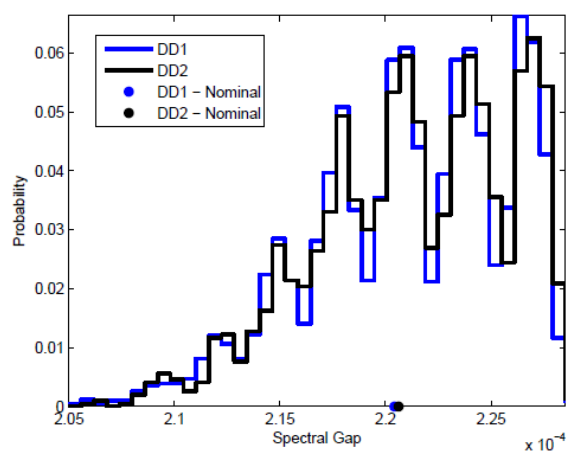
Zone air states

Construction surface states

A matrix of Dynamics in an EnergyPlus model

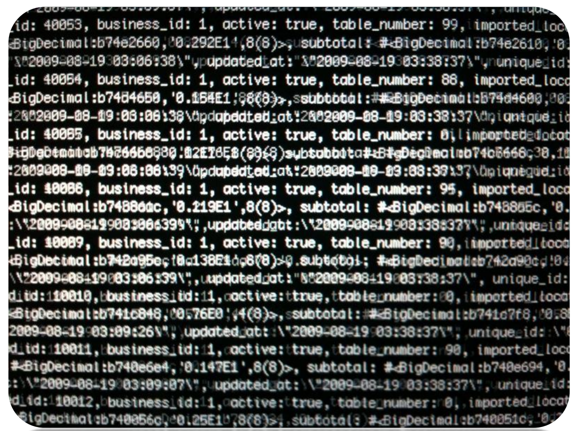
Sorted based on interconnection matrices





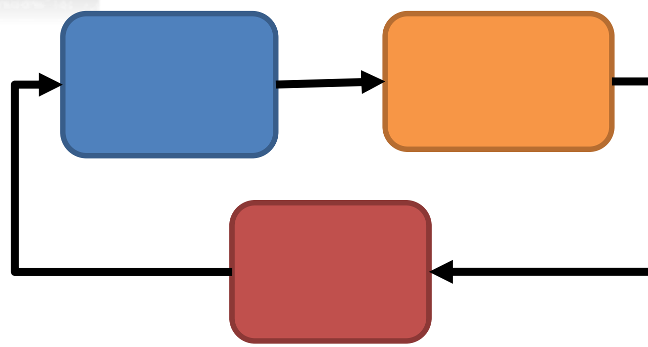
Uncertainty in spectral gap of the graph Laplacian illustrates robustness of interconnectivity of energy dynamics

- Modeling

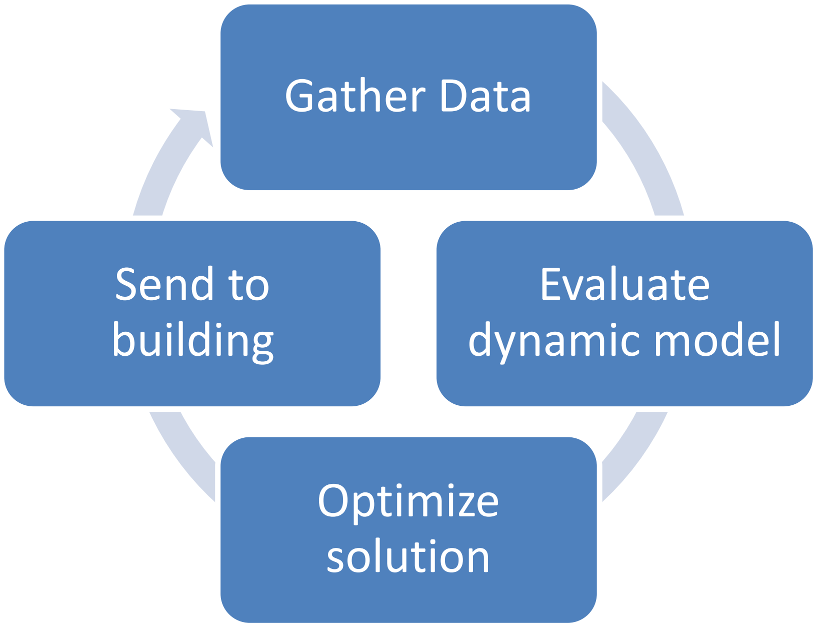


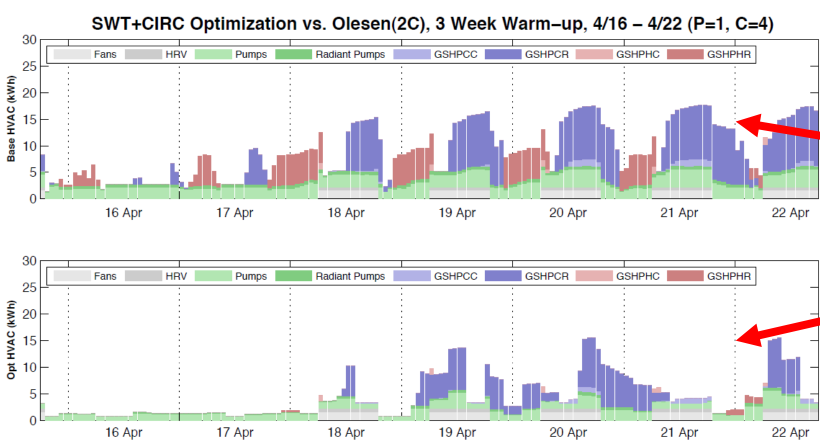
- Data

- Control



Model Predictive Control





Base Case

Model based optimization

Corbin 2011

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

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Questions?

Acknowledgements

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This work was partially supported under the contracts:

W912HQ-09-C-0054 Project Number: SI-1709 administered by SERDP technology program of the Department of Defense.

Army Research Office
Grant W911NF-11-1-0511, with Program Manager Dr. Sam Stanton.

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