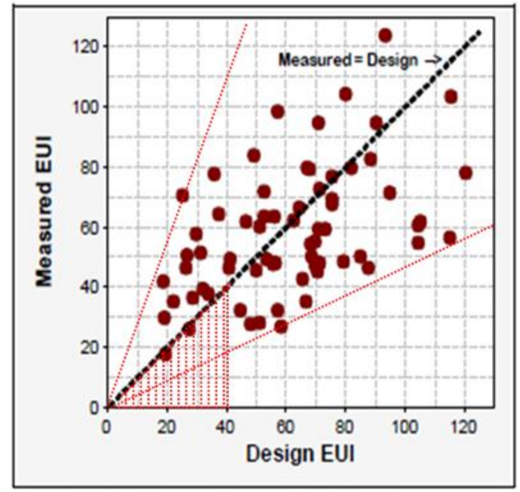
Modeling and Simulation of Human Behavior in Buildings

2015 Building Technologies Office Peer Review

Energy-related occupant behavior in buildings, e.g.:

- Open/close windows
- Switch/dim lights
- Adjust thermostat
- Move around
- Turn on/off HVAC
- Operate shades



2008 NBI Study of LEED NC certified buildings

BERKELEY LAB
Lawrence Berkeley National Laboratory

Bentley

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Project Summary

Timeline:

Start date: 1/1/2013

Planned end date: 12/31/2015

Key Milestones

1. Behavior framework; 12/2013
2. IEA EBC Annex 66; 11/2013, 11/2014
3. Behavior workshops; 8/2014, 3/2015
4. Behavior modeling tool; 2/2015
5. Behavior XML schema; 3/2015

Budget:

Total DOE $ to date: **$380k (FY13+FY14)**

Total future DOE $: **$100k (FY15)**

Target Market/Audience:

- Commercial and multi-family residences
- New construction and existing buildings
- Energy modelers

Key Partners:

U.S. Partners	China Partners
Bentley Systems	Tsinghua University
	Center of Building Standards
	Center EEB

Project Goal:

1. Improve data and assumptions of occupant behavior for building energy modeling
2. Develop tools
   - An XML schema to describe occupant behavior
   - A modeling tool for simulating behavior
3. Integrate the tools with EnergyPlus to improve simulation of behavior impacts on building energy use and technology performance

Purpose and Objectives

Problem Statement:

- Occupant behavior in buildings is not well understood and oversimplified!
- Occupants play an essential role in building design and operation.
- Strong need of behavior data, modeling tools and case studies.

Target Market and Audience:

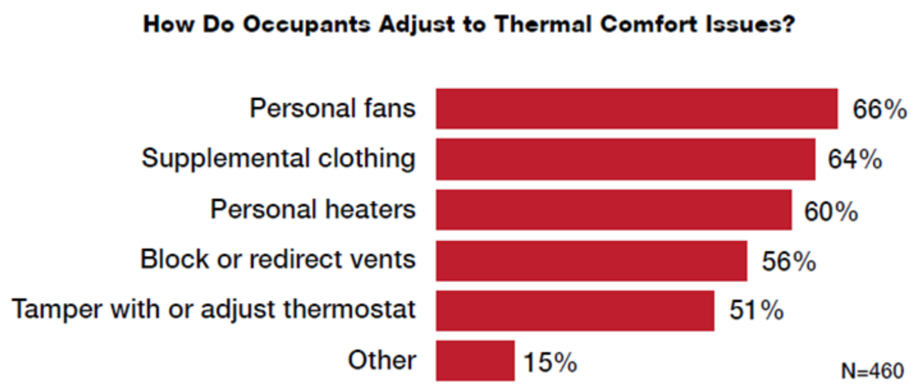
- Commercial & residential buildings; New construction & existing buildings;
- Size of Market: 24 Quads Total (2.2 Quads U.S. homes)
- Energy modelers

Impact of Project:

- The developed occupant behavior tools will enable more accurate consideration of behavior in building performance simulation
- Case studies and workshops demonstrated the use of these behavior tools to improve building design and operations
- Contribution to ASHRAE Handbook Fundamental 2017
- Contribution to IEA EBC Annex 66

Complexity of Human Behavior

- Inherent uncertainty
- Multi-disciplinary
- Various driving factors:
  - Individual: culture, lifestyle, habit, environmental awareness
  - Temporal: time of the day, day of the week, season
  - Spatial: office, home, …
  - Indoor and outdoor environmental conditions
- Very limited data to help us understand



IFMA 2009 HVAC Survey of IFMA members in US and Canada with 452 responses from 3357 samples

Diverse ways to turn on air-conditioning (China Survey Results):

- always turn on
- turn on when entering
- turn on when feeling hot
- turn on before sleep
- never turn on
- randomly turn on

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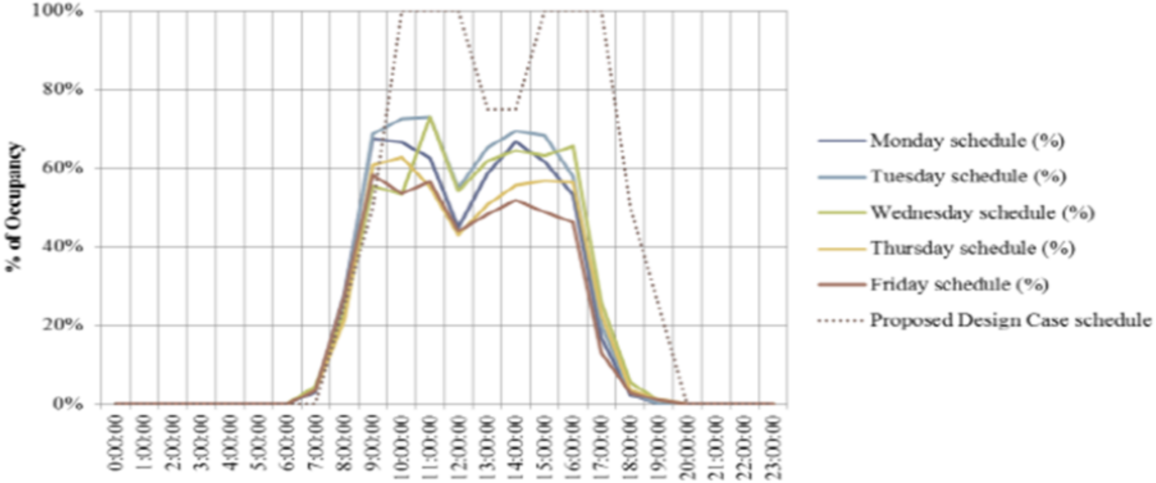
Limitations of occupant related input in current BEM programs

- Deterministic or fixed settings and rules
- Homogeneous profiles or schedules
- Implicit assumptions
  - ❖ Behavior input defined at physical (e.g. Windows , Shades) objects rather than People objects. EnergyPlus as an example.
- Use of custom features needs advanced skills; custom features are not robust.
  - ❖ EnergyPlus EMS (Energy Management System)
  - ❖ DOE-2 User Function



K.P. Lam et al. An EnergyPlus whole building energy model calibration method for office buildings using occupant behavior data mining and empirical data. 2014 ASHRAE/IBPSA-USA Building Energy Modeling Conference.

Approach

Data Driven	**Identify, understand and describe energy-related occupant behavior by data analytics**
Standard	**Develop a DNAs (Drivers, Needs, Actions, Systems) framework to standardize the representation of occupant behavior in buildings**
Robust Modeling	**Develop and integrate behavior modeling tool into whole building performance simulation (EnergyPlus)**
Provide Insights	**Evaluate the impact of behavior on building energy use and performance of building technologies using case studies**

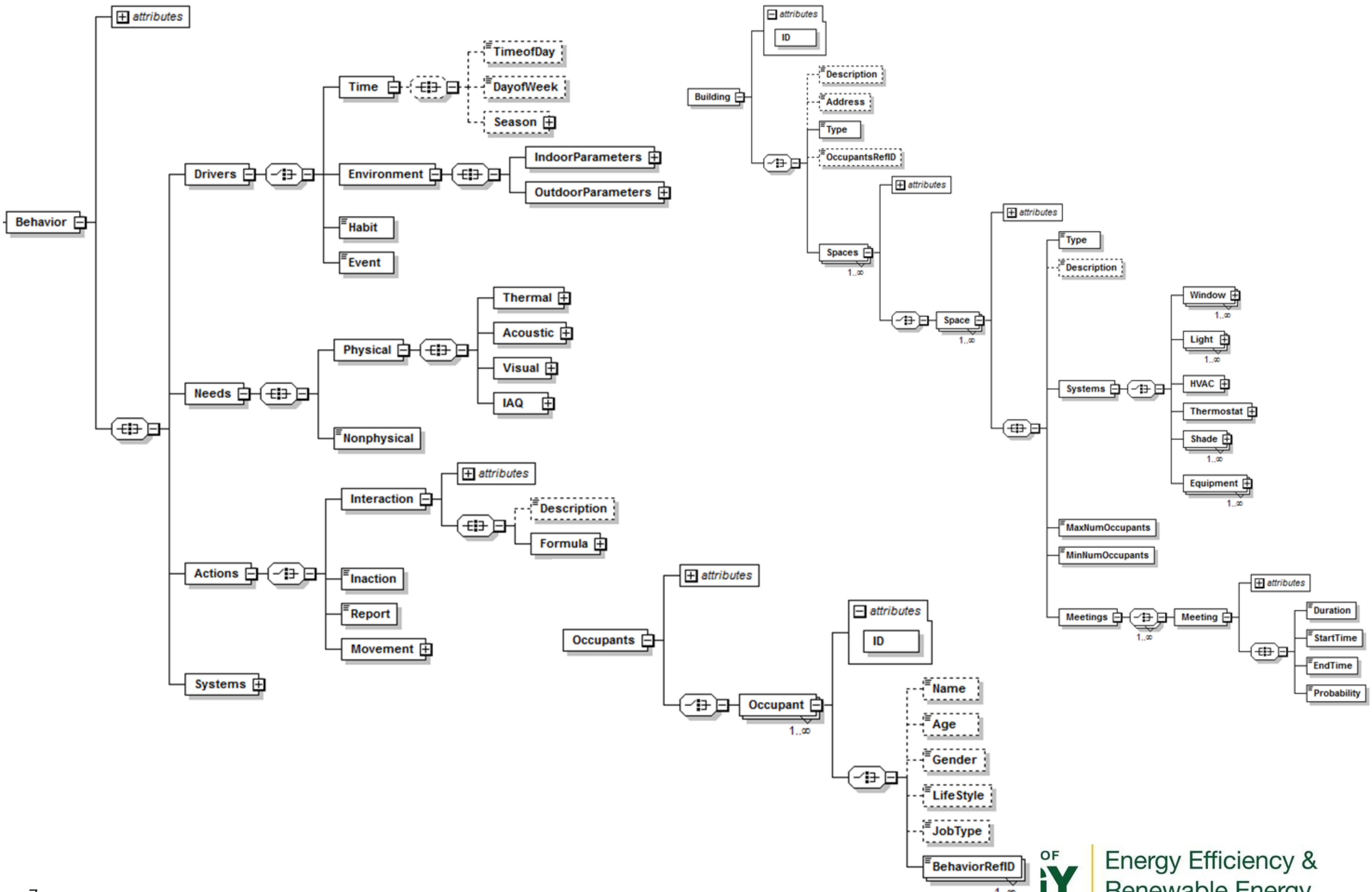
Distinctive Characteristics:

- Advanced data mining methods to discover behavior patterns
- A framework and XML schema to describe occupant behavior
- A behavior modeling tool to enable co-simulation
- Integration with EnergyPlus to simulate behavior impact

Key Issues:

- Complexity and multi-disciplinary of occupant behavior
- Behavior data: hard to get, privacy concerns

The XML Schema (obXML) representing Occupant Behavior



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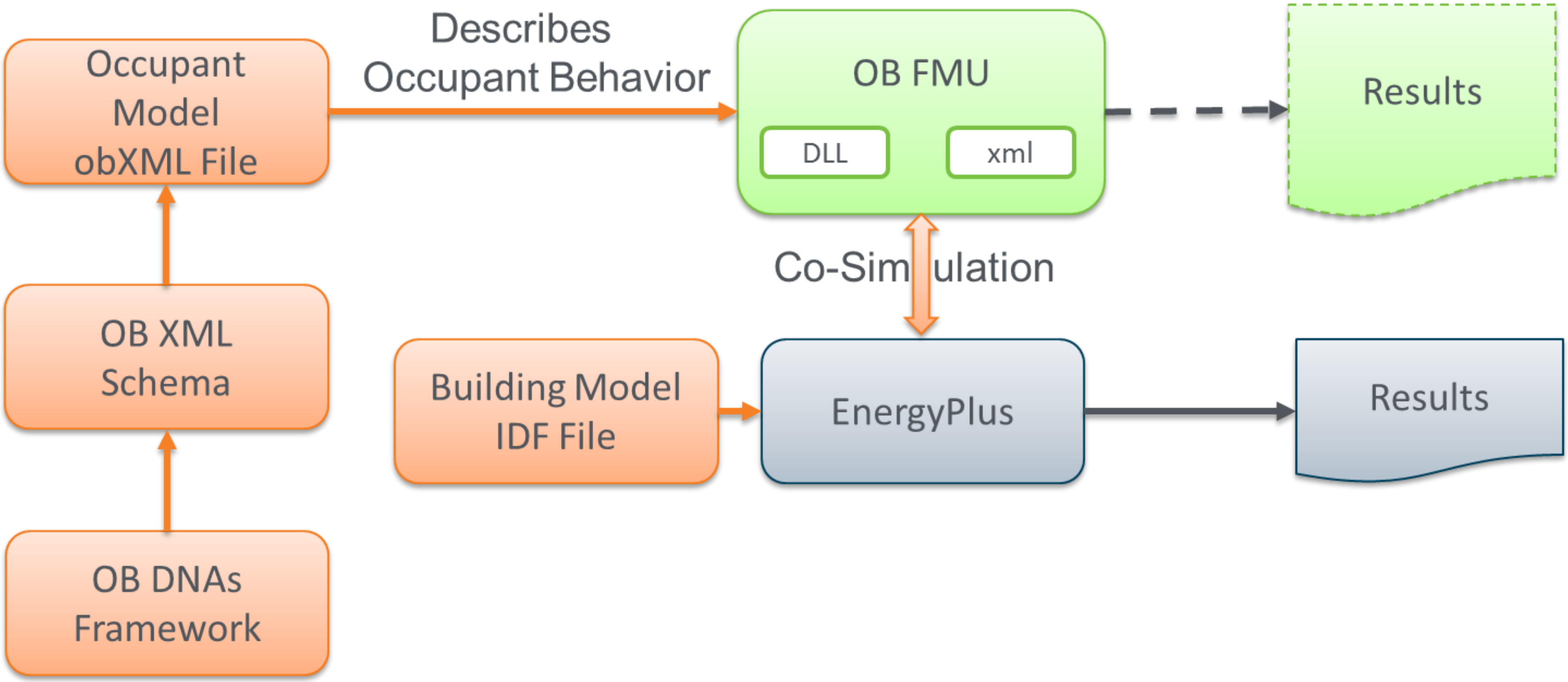
Architecture of the Occupant Behavior Modeling Tool



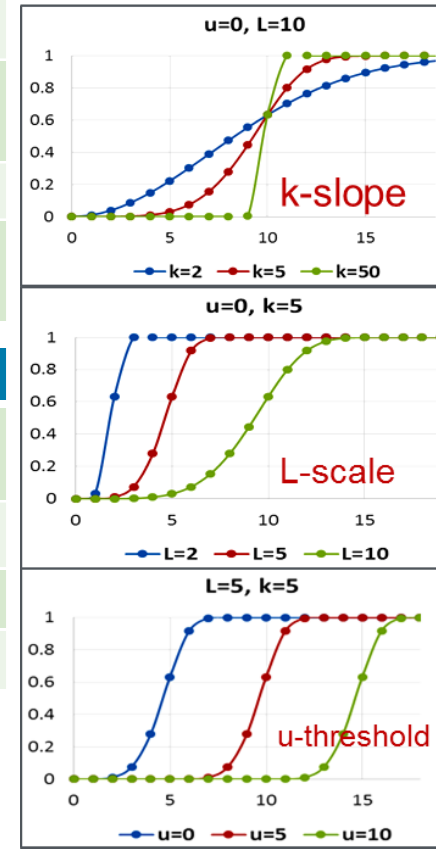
A new and unique behavior modeling tool enabling co-simulation

Example: Models of Air-Conditioning On/off

No.	Turn on pattern description	Model
1	Never turn on AC	$P = 0$
2	Turn on AC when occupied and feeling hot	$P = \begin{cases} 1 - e^{-\left(\frac{T-u}{L}\right)^k \Delta\tau}, T \geq u \\ 0, T < u \end{cases}$ *, when occupied*
3	Turn on AC when entering the room and feeling hot	$P = \begin{cases} 1 - e^{-c\left(\frac{T-u}{L}\right)^k}, T \geq u \\ 0, T < u \end{cases}$ *, when entering*
4	Turn on AC when entering the room	$P = P_{enter}$
5	Turn on AC when working time begins	$P = P_{on\_time}$

No.	Turn off pattern description	Model
1	Turn off AC when feeling cold enough	$P = \begin{cases} 1 - e^{-\left(\frac{u-T}{L}\right)^k \Delta\tau}, T \leq u \\ 0, T > u \end{cases}$ *, when occupied*
2	Turn off AC when leaving the room	$P = 1 - e^{-\left(\frac{t_{leave}}{L}\right)^k}$
3	Turn off AC when working time ends	$P = P_{off\_time}$
4	Never turn off AC	$P = 0$

$$P = \begin{cases} 1 - e^{-\left(\frac{x-u}{L}\right)^k \Delta\tau}, x \geq u \\ 0, x < u \end{cases}$$



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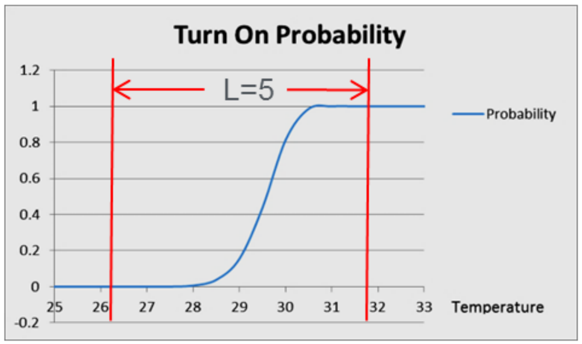
Example: AC Results

- **AC On model**
  - ✓ Turn on when entering the room
  - ✓ Turn on when feeling hot

Turn on AC when feeling hot

Δt=10 min
u=26, l=5, k=8

T=30 -> P=0.81

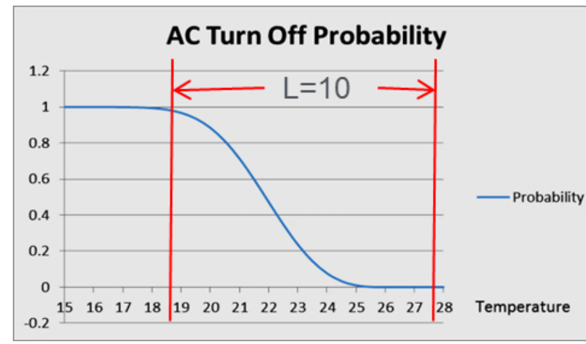


- **AC Off model**
  - ✓ Turn off when leaving the room
  - ✓ Turn off when feeling cold

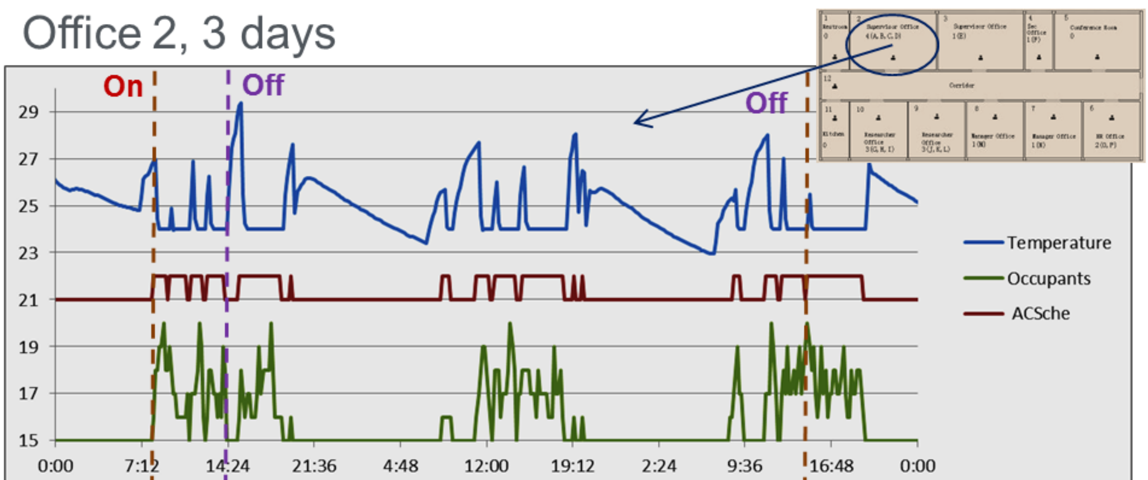
Turn off AC when feeling cold

Δt=10 min
u=26, l=10, k=3

T=24 -> P=0.08



Office 2, 3 days



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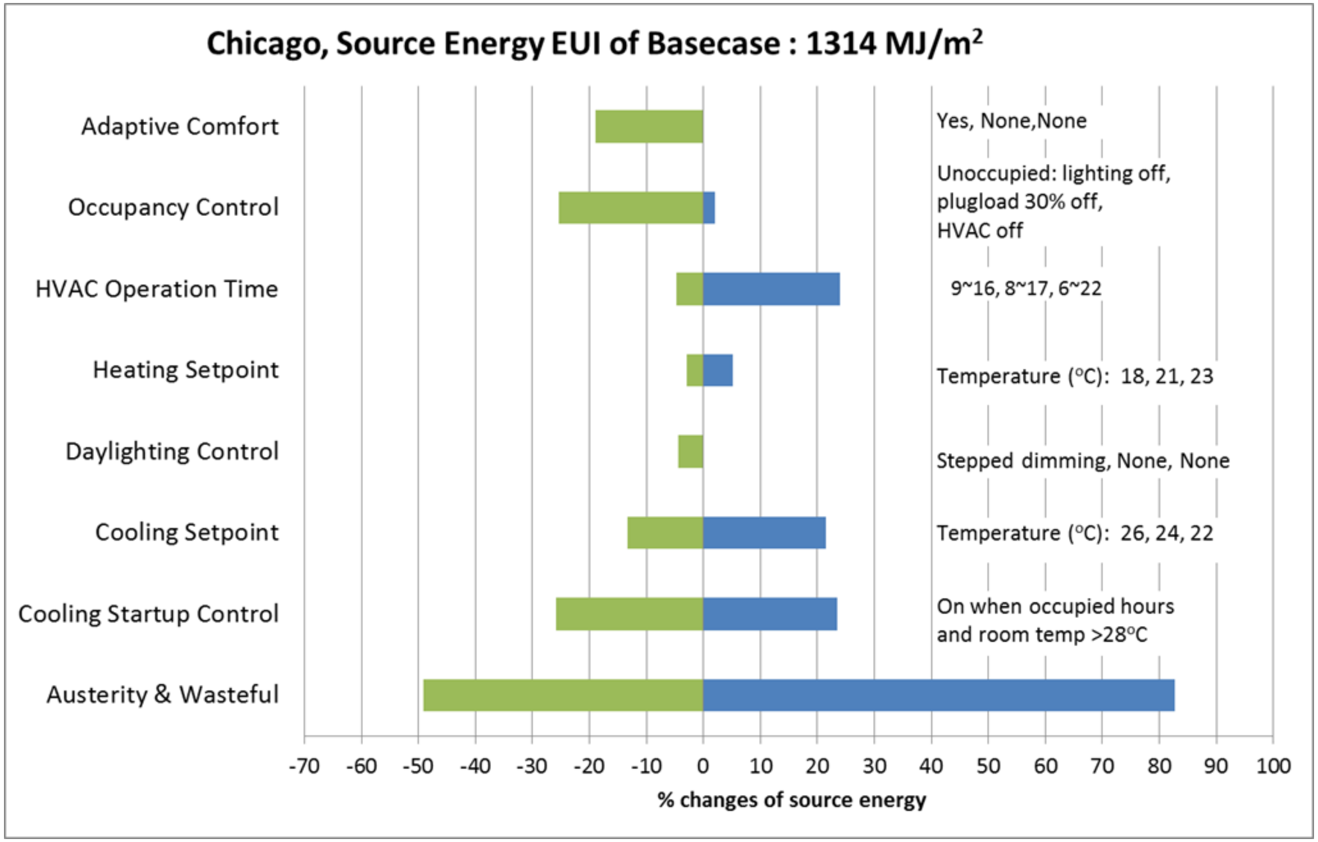
Occupant Behaviors in Private Offices

Behavior	Austerity Lifestyle	Standard Lifestyle	Wasteful Lifestyle
Cooling Setpoint (^oC)	26	24	22
Heating Setpoint (^oC)	18	21	23
HVAC Operation Time (Cooling and Heating)	9:00am - 4:00pm	8:00am - 5:00pm	6:00am - 10:00pm
Occupancy Control	If unoccupied • Lighting: off • Plug-load: 30% off • HVAC: off	Scheduled	If unoccupied • Lighting: on • Plug-load: on • HVAC: on
Cooling Startup Control	Cooling starts when $T_{zone, air} \geq 28^oC$ during occupied hours, once started maintains the cooling setpoint; Cooling off during unoccupied hours.	Follow fan schedule & cooling thermostat during 8:00am - 5:00pm	Cooling always on during 6:00am - 10:00pm
Daylighting Control	Stepped Dimming	None	None
Adaptive Comfort	Yes	None	None

Impact of Occupant Behavior on Energy Use in Private Offices



- Assumed three life/work styles: Austerity, Norm, and Wasteful
- Simulation results for a single-person office in Chicago
- Energy impact
  - Austerity cuts energy use by 50%
  - Wasteful increases energy use by 80%

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Progress and Accomplishments

Lessons Learned: Perceived complexity and usefulness of research; Lack good data

Accomplishments:
Evaluated impact of occupant behavior on energy use in buildings
Developed a software tool of behavior models
Developed a DNAs framework and XML schema for human behavior
Enabled EnergyPlus to co-simulate with the behavior modeling tool

Market Impact:

- Estimated potential of energy savings from behavior efficiency measures:
  - Residential Sector: 10% to 20%[1] (2.2 Quads from US homes)
  - Commercial Sector: 5% to 30%[2]
- Benefit to the U.S. and China:
  - Improve building simulation with better assumptions of occupant behavior
  - Provide feedback to technology development and building design

Awards/Recognition:

- Co-founding and leading the IEA EBC Annex 66

[1]Heck S. and Tai H (McKinsey & Company): *Sizing the potential of behavioral energy-efficiency initiative in the US residential market*, Report, 2014.
[2]Hong T. and Lin H-W: *Occupant Behavior: Impact on Energy Use of Private Offices*. LBNL Report, LBNL-6128E, 2013.

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Project Integration and Collaboration

Project Integration:
- Actively engage with Bentley Systems during the project
- 7 public workshops and seminars with stakeholders
- Leverage on international effort through Annex 66

EBC
Energy in Buildings and Communities Programme

IEA-EBC Annex 66
Definition and Simulation of Occupant Behavior in Buildings

Partners, Subcontractors, and Collaborators:
- A project under the U.S.-China CERC program
- **U.S. partners:** Bentley Systems
- **China partners:** Tsinghua University, CEEB of MoHURD, CBS

Communications:
- 7 public workshops and seminars: LBNL 7/2013; China 10/2013; IEA 8/2013; LBNL 8/2014; ASHRAE: 6/2014 Seattle, 1/2015 Chicago; LBNL 3/2015.
- Behavior modeling text for ASHRAE Handbook Fundamental 2017
- Presentations at conferences: BECC, ASHRAE, IBPSA, EDRA
- Publications: 12 journal articles, 5 conference papers
- IEA EBC Annex 66 meetings

Next Steps and Future Plans

Next Steps:

- Conduct a simulation-based case study to look at impact of occupant behavior on building performance and energy savings of technology
- Refine and publish the behavior schema and modeling tool
- Continue collaboration with Annex 66
- Outreach to ASHRAE standards (90.1, 189.1, 62.1, 55) committees

Future Plans:

1. Promote the developed behavior tools
2. Synergy with related behavior research and programs: utilities, ASHRAE, ACEEE, code and standards, policy
3. Coordinate with related activities under BTO programs
4. Modeling behavior at-scale: community, district energy systems
5. Integrate occupant behavior XML schema with BIM
6. Study impact of occupant behavior on demand response

Reference Slides

Project Budget

Project Budget:

2013: $160K

2014: $220K

2015: $100K

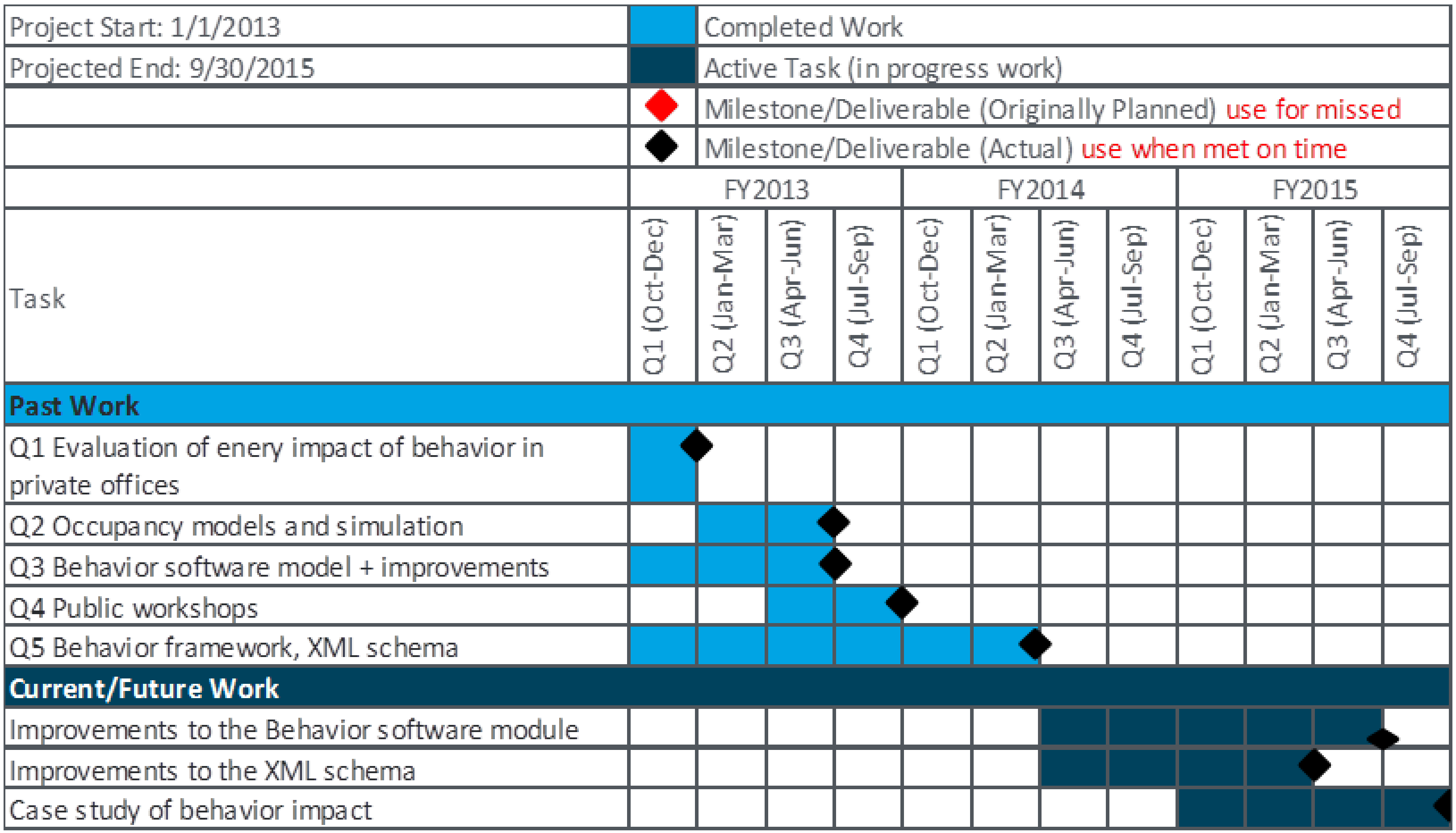
Variances: The budget for 2015 was cut and the scope was adjusted.
Cost to Date: 2014: 100%; 2015: 30%
Additional Funding: NA

Budget History					
Jan 2013 – FY2014 (past)		FY2015 (current)		FY2016 – FY2020 (planned CERC 2.0)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$380K	$400K	$100K	$100K	tbd	tbd

Project Plan and Schedule

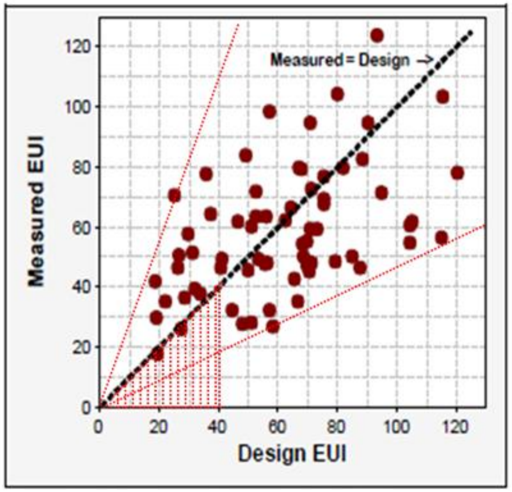
Project plan:

- Start date: 1/1/2013
- Completion date: projected 12/31/2015



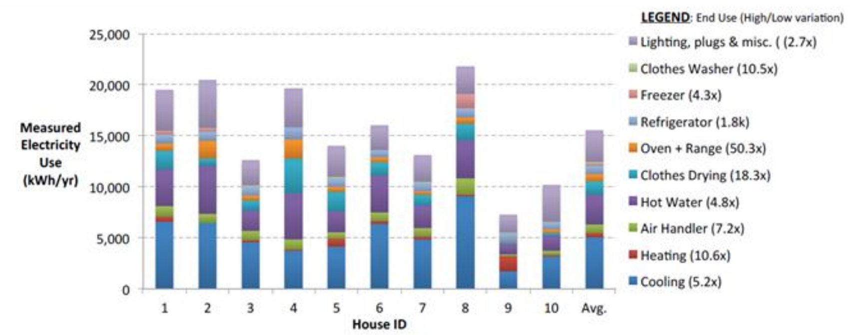
Background

- Technologies alone do not necessarily guarantee low energy use in buildings.
- Human behavior :
  - Not well understood
  - Stochastic and multidisciplinary
  - Usually over-simplified or ignored!
- Behavior changes, usually no or low cost, has demonstrated:
  - 30% energy savings in buildings
  - > 50% in very low energy buildings.



2008 NBI Study of LEED NC certified buildings

- Low energy buildings under-performed



Courtesy: Danny Parker, FSEC

- Virtually identical homes and efficiencies
- 3x variation in energy use

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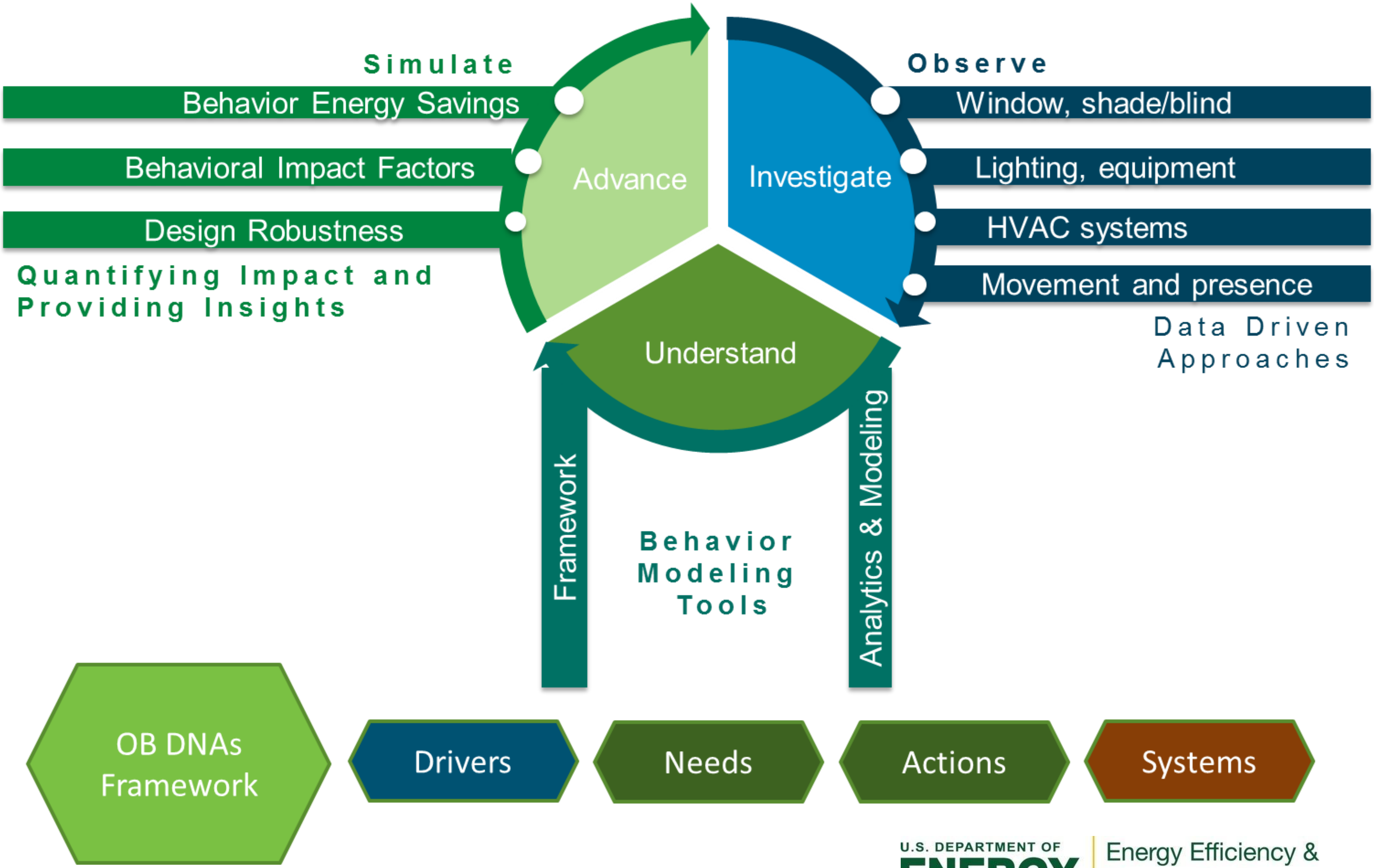
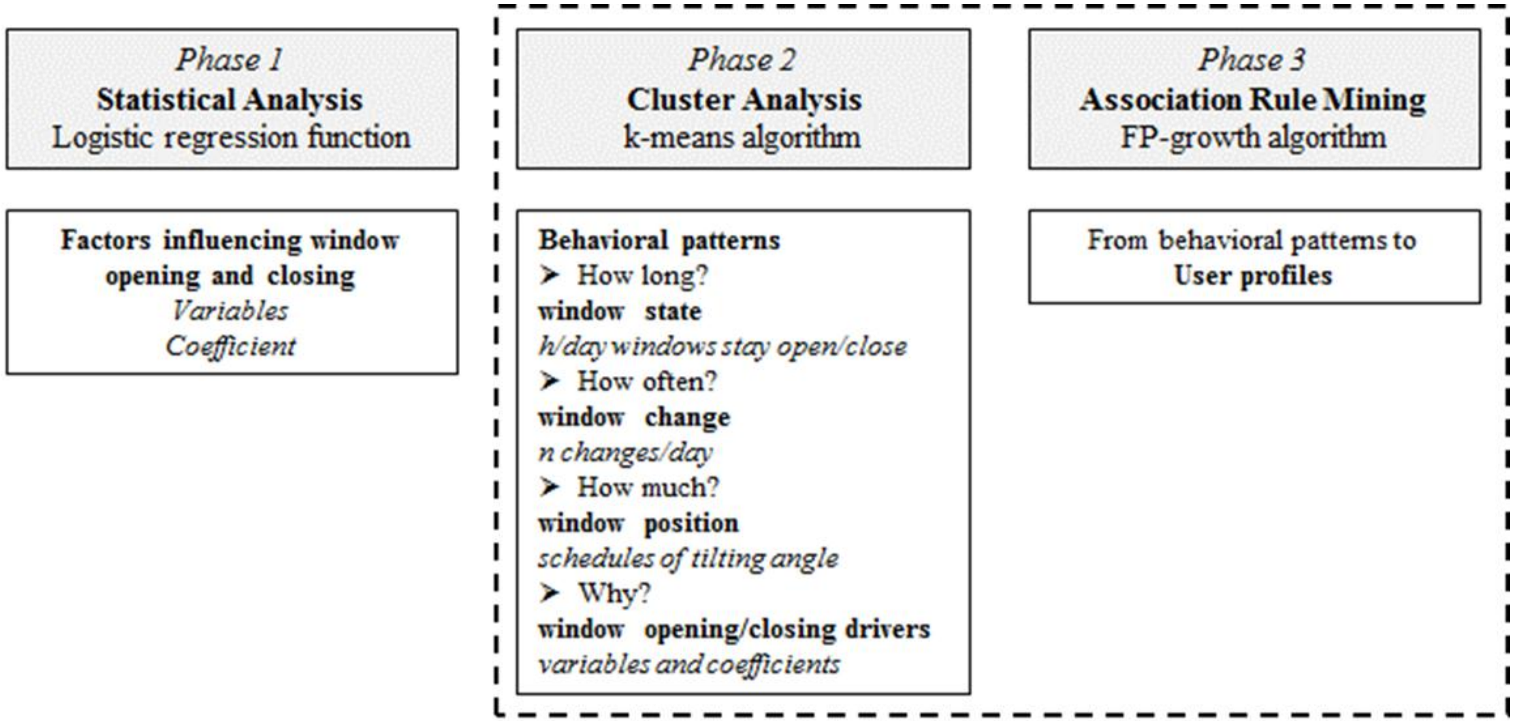
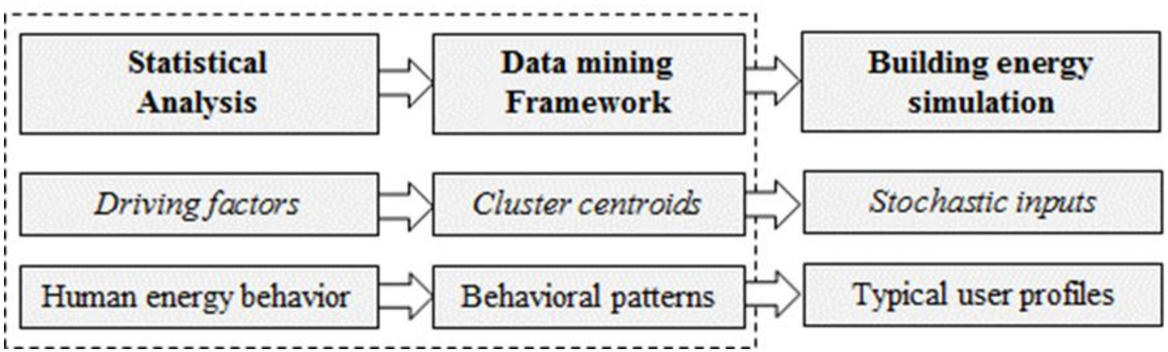
Technical Approaches



Data Mining and Statistical Methods –

Occupant Behavior of Window Opening/Closing

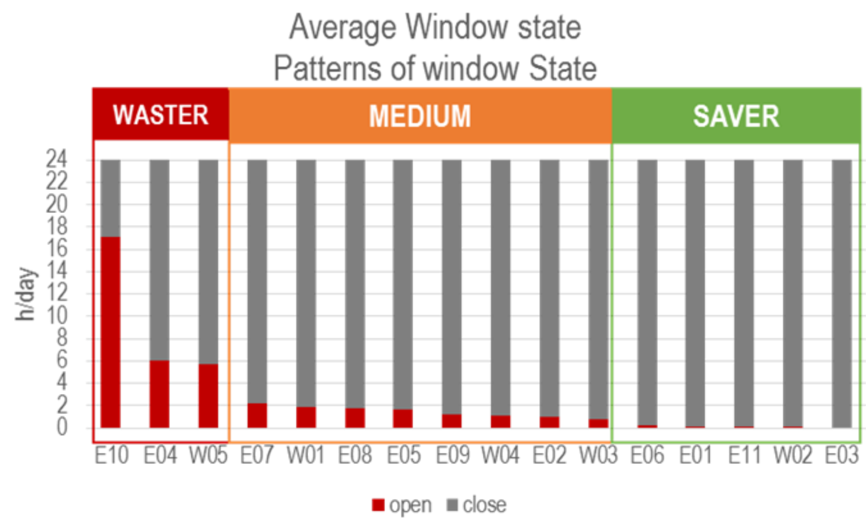


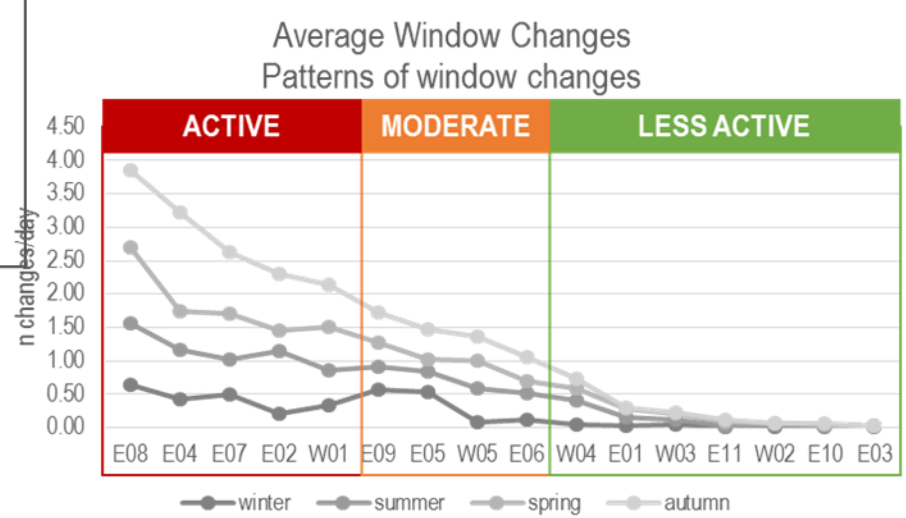


Dataset and Results

- 16 offices of a natural ventilated building
- 5-minute interval data over two complete years
- measured indoor and outdoor physical parameters
- measured behavior and energy use

Outdoor	Indoor	Behavior and Energy Use
Solar radiation [W/m²]	Room air temperature [°C]	Occupancy [0/1]*
Rain – amount [l/m²]	Surface temperature [°C]	Window contact [0/1 ; Reed contacts]*
Rain – event [yes/no]	Ceiling slab temperature [°C]	Top light control [0/1 ; Reed contacts]*
Light intensity – horizontal [lx]	CO_2 concentration [ppm]	Sun protection [% of closure: 0% = open to 100% = closed]
Light intensity - South [lx]		Electricity consumption [kWh]
Light intensity - East [lx]		
Light intensity - North [lx]		
Light intensity - West [lx]		
Outdoor temperature [°C]		
Wind – velocity [m/s]		
Wind – direction [°]		
CO_2 content in air [ppm]		
Outdoor humidity [%rH]		





Publications - Journal articles

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2. T. Hong, S. Taylor-Lange, S. D'Oca, D. Yan, S. Corgnati. Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings. Energy and Buildings, under review, 2015.
3. T Hong, S D'Oca, W Turner, S Taylor-Lange. An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs Framework. Building and Environment, 2015.
4. X. Ren, D. Yan, T. Hong. Data Mining of Space Heating System Performance in Affordable Housing. Building and Environment, 2015.
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7. S. D'Oca, T. Hong. A data-mining approach to discover patterns of window opening and closing behavior in offices. Building and Environment, 2014.
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9. C. Li, T. Hong, D. Yan. An insight into actual energy use and its drivers in high-performance buildings, Applied Energy, 2014.
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11. H.W. Lin, T. Hong. On Variations of Space-heating Energy Use in Office Buildings, Applied Energy, 2013.
12. W.K. Chang and T. Hong. Statistical Analysis and Modeling of Occupancy Patterns in Open-Plan Offices using Measured Lighting-Switch Data, Journal of Building Simulation, 2013.