Hardware-in-the-loop Laboratory Performance Verification of Flexible Building Equipment in a Typical Commercial Building (HILFT)

U.S. DOE DE-EE0009153

Updates for the Industry Advisory Board

July 2024

Building Science & Engineering Group
Drexel University

DREXEL UNIVERSITY
College of
Engineering

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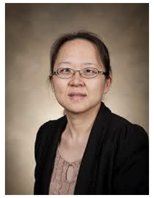
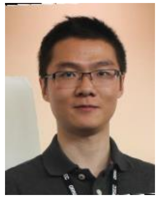

Zheng O’Neill


Zhiyao Yang


Caleb Calfa

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Steven Bushby


Amanda Pertzborn


Vance Payne

Agenda

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Engineering Group
Drexel University

- Background & Summary
- Method
  - Testbeds
  - Testing Scenarios
  - Postprocess Procedure
  - Data Schema
- Technical Validation
  - Uncertainty Analysis
  - Data Quality Control
  - Evaluation of Demand Flexibility
- Conclusion
- Discussions

Background & Summary: Goal

Potential

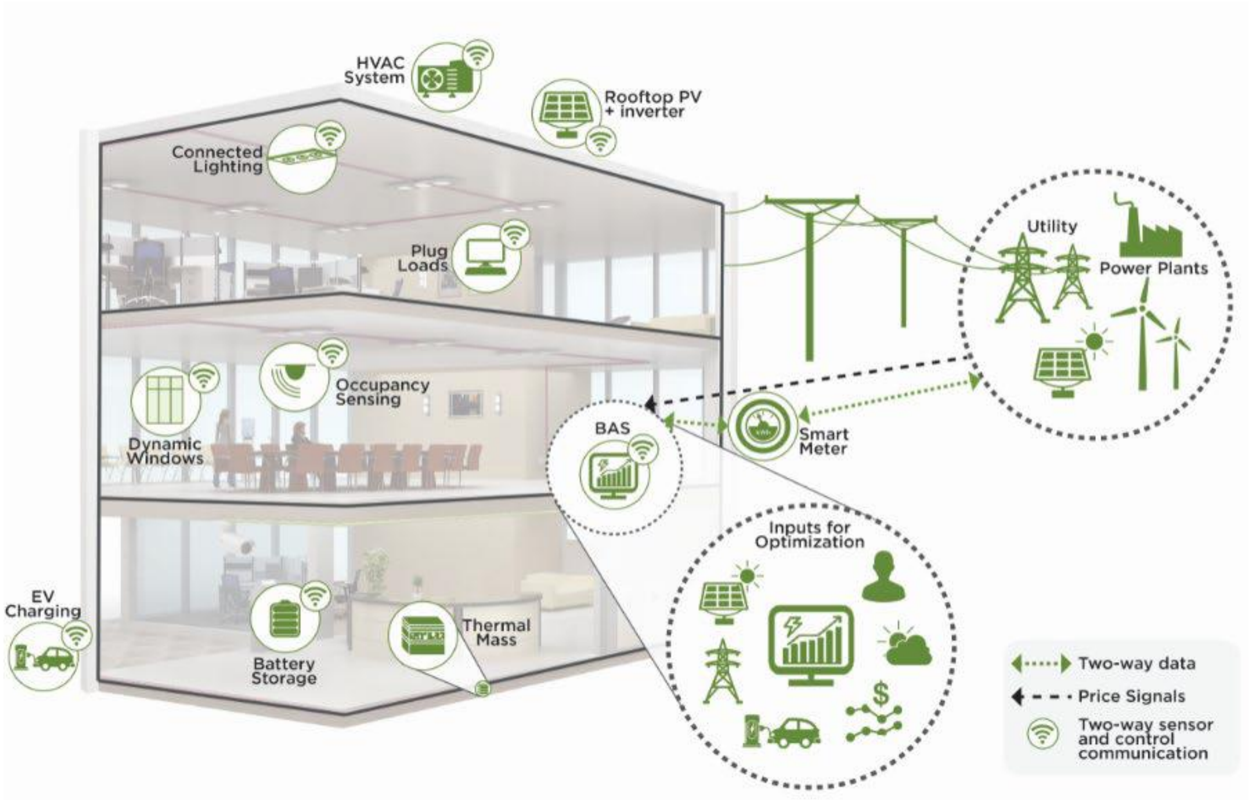
- buildings and building equipment can provide flexible electrical loads

Challenge

- lack of high-resolution end-use load and energy savings shape data

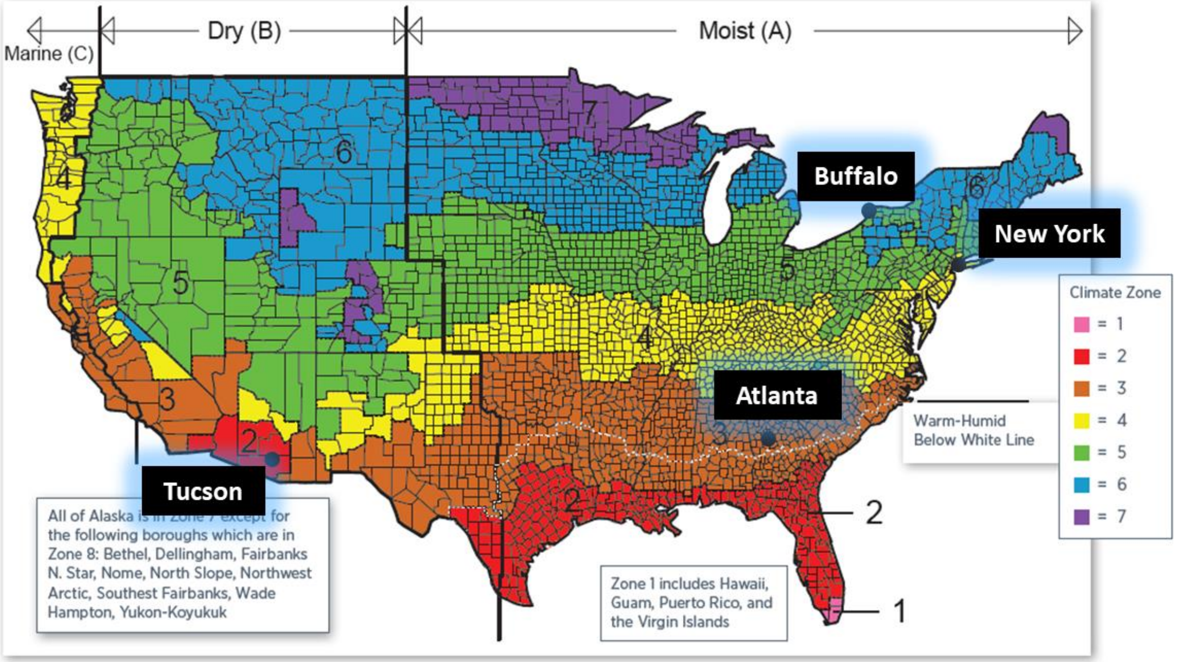
Goal

- publicly-available, high-fidelity datasets
- commonly-used commercial building HVAC and thermal storage equipment

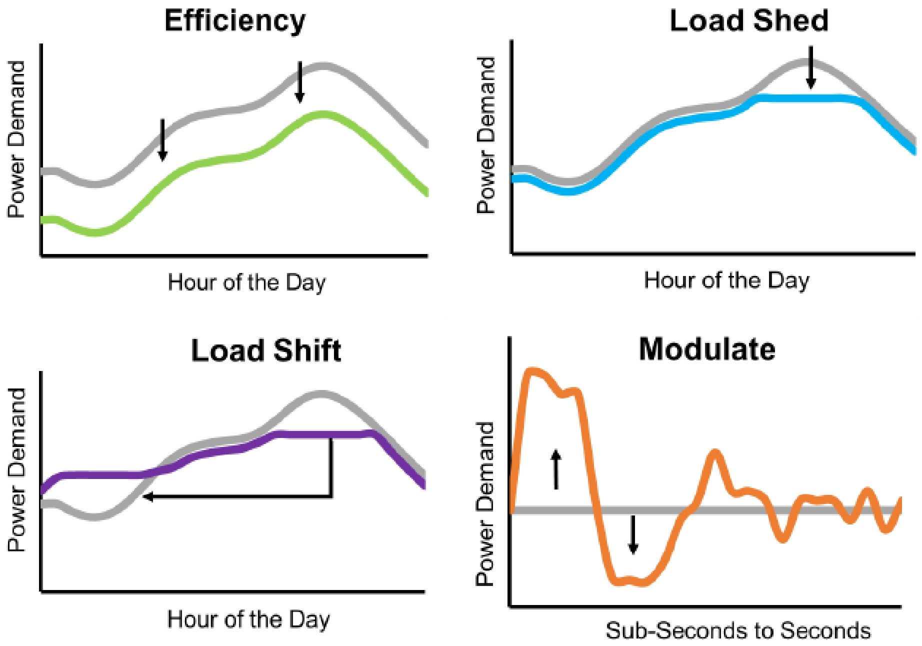


Example grid-interactive efficient commercial building [1]

Background & Summary: Scope



IECC climate zone map [2]



Building flexibility load curves [1]

Weather	Building Type	Control	System	Occupancy	Behavior
Typical summer	90.1-2004	Heuristic rule	No TES	Typical	Typical
Extreme summer, typical winter (HP only)/shoulder	90.1-2019	MPC	TES	Dense (1.5 x typical)	Energy Saving

Background & Summary: Scope

- Intelligent Building Agents Laboratory (IBAL) facility at NIST [3]
  - Chiller
  - Ice thermal storage tank
  - AHU-VAV
- Heat Pump Environmental Testing Facility (ASHP) at NIST
  - Two-stage air-source heat pump
- Heat Pump Environmental Testing Facility (WSHP) at TAMU
  - Variable speed water-source heat pump


AHU

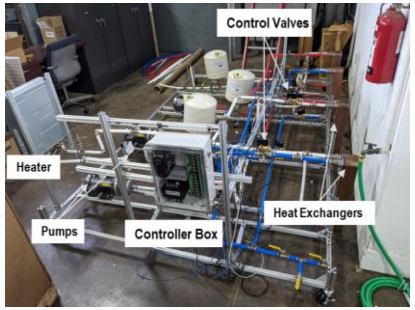

VAV


Chiller


Ice tank


Air-source heat pump indoor unit being installed

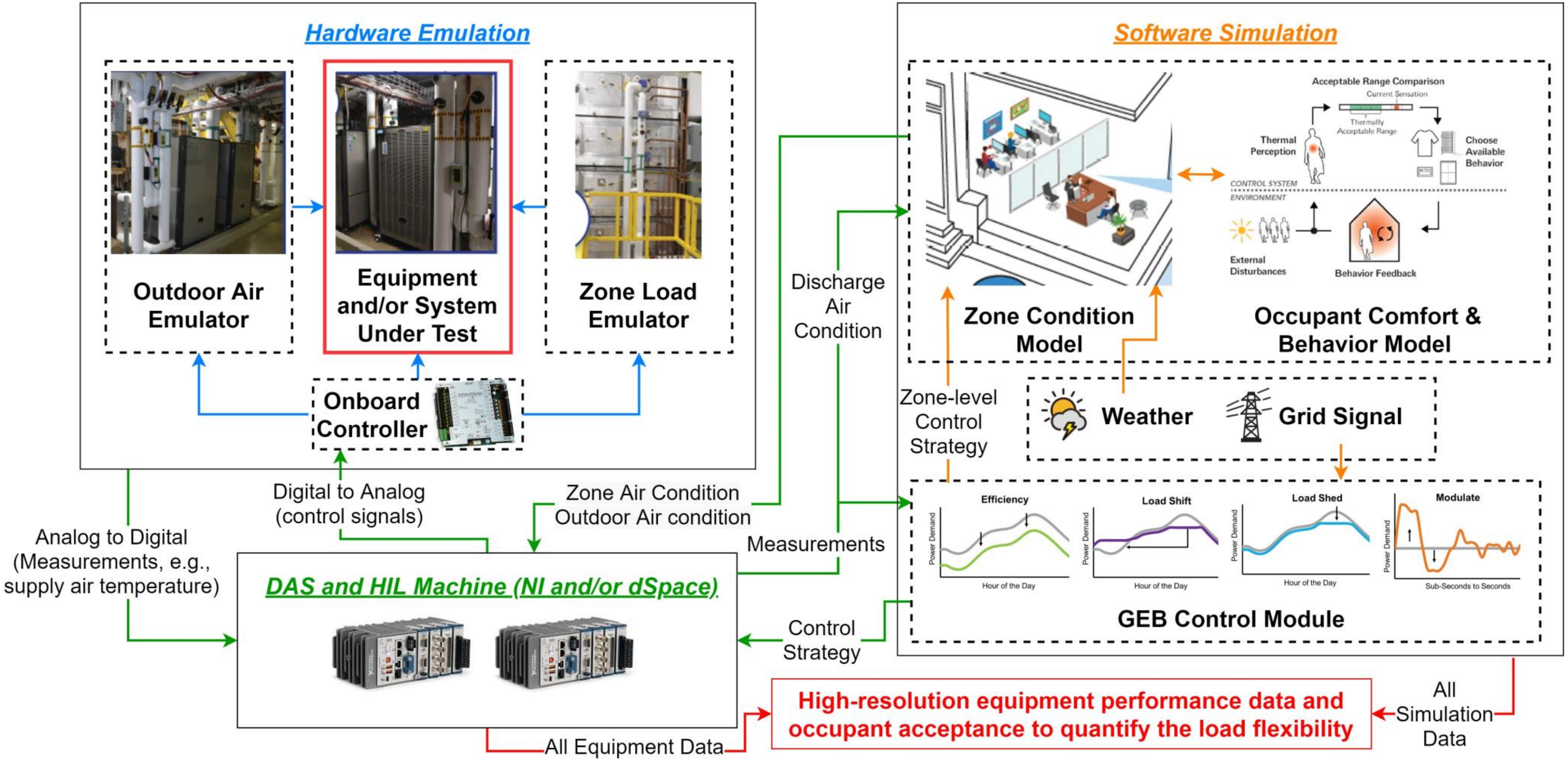

Air-source heat pump outdoor unit being installed



Water-source heat pump hydronic system


Water-source heat pump

Method: Testbed



Hardware Emulation

Outdoor Air Emulator

Equipment and/or System Under Test

Zone Load Emulator

Onboard Controller

Digital to Analog (control signals)

Analog to Digital (Measurements, e.g., supply air temperature)

Zone Air Condition
Outdoor Air condition

DAS and HIL Machine (NI and/or dSpace)

Discharge Air Condition

Measurements

Control Strategy

All Equipment Data

Software Simulation

Zone Condition Model

Occupant Comfort & Behavior Model

Zone-level Control Strategy

Weather

Grid Signal

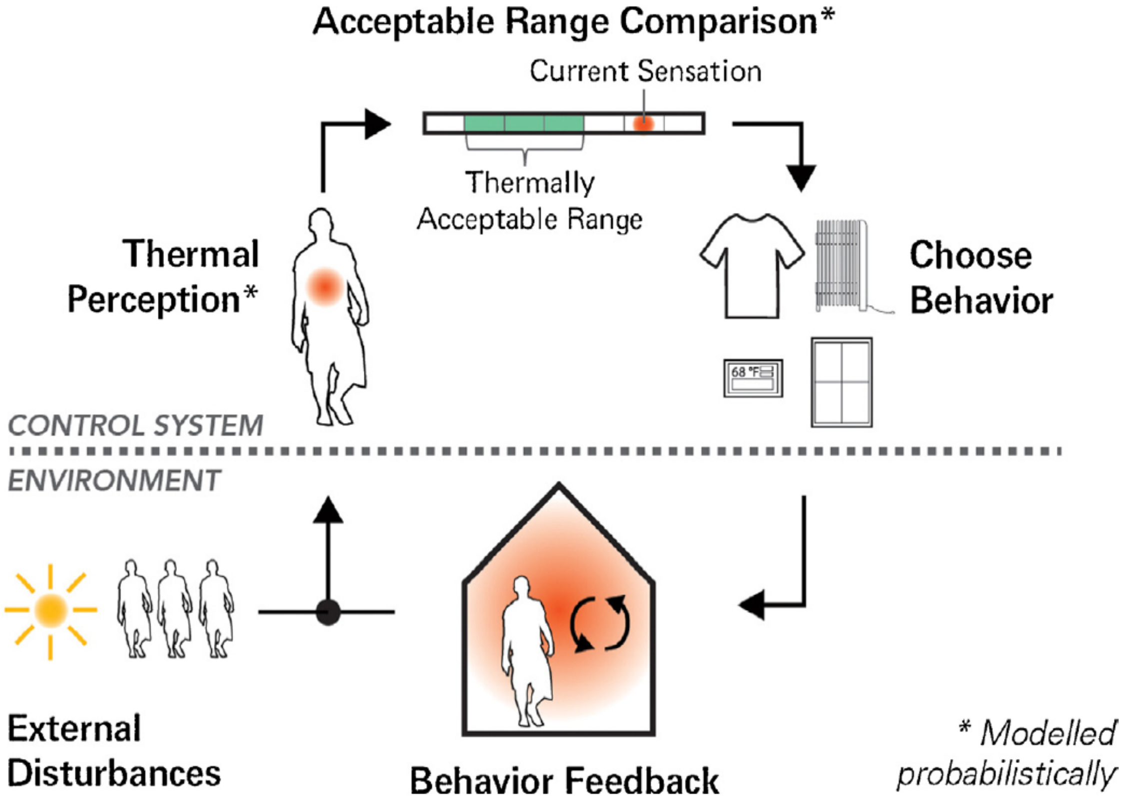
GEB Control Module

All Simulation Data

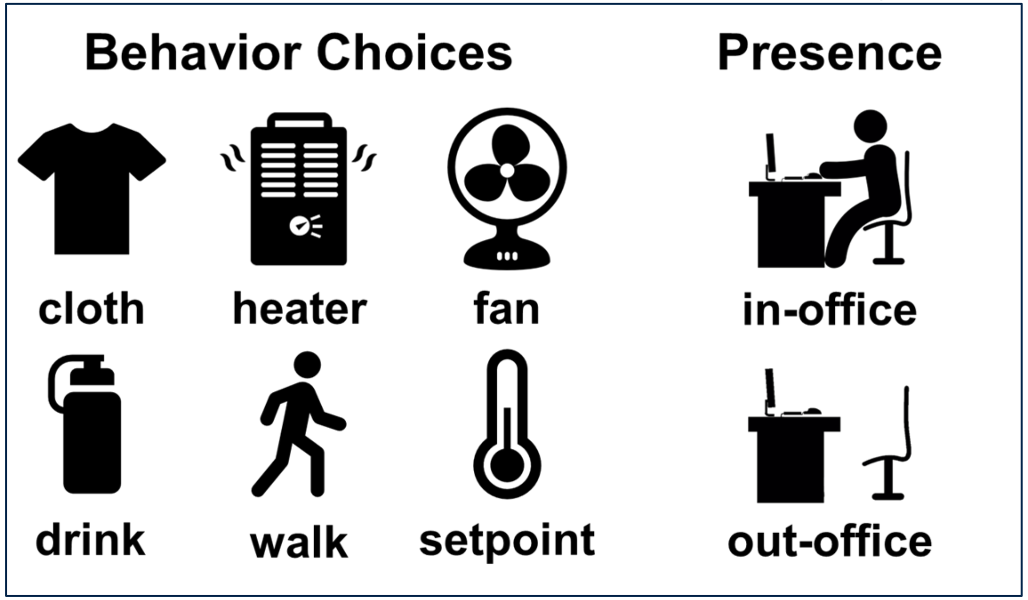
High-resolution equipment performance data and occupant acceptance to quantify the load flexibility

Virtual Building: Occupant Behavior Model

Adapt an existing field validated agent-based occupant thermal behavior model [6]

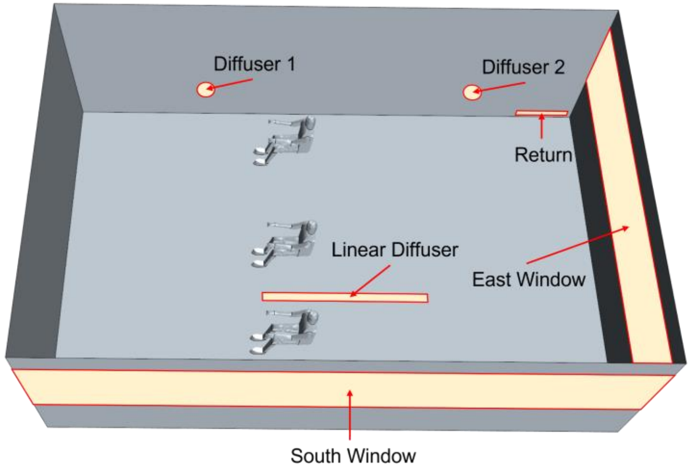


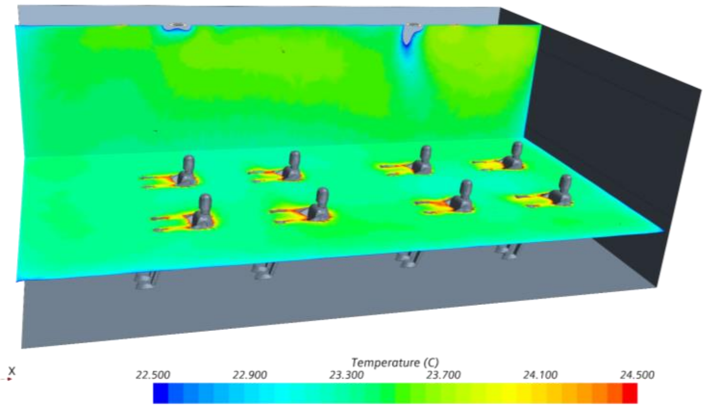
Behaviors considered in this study

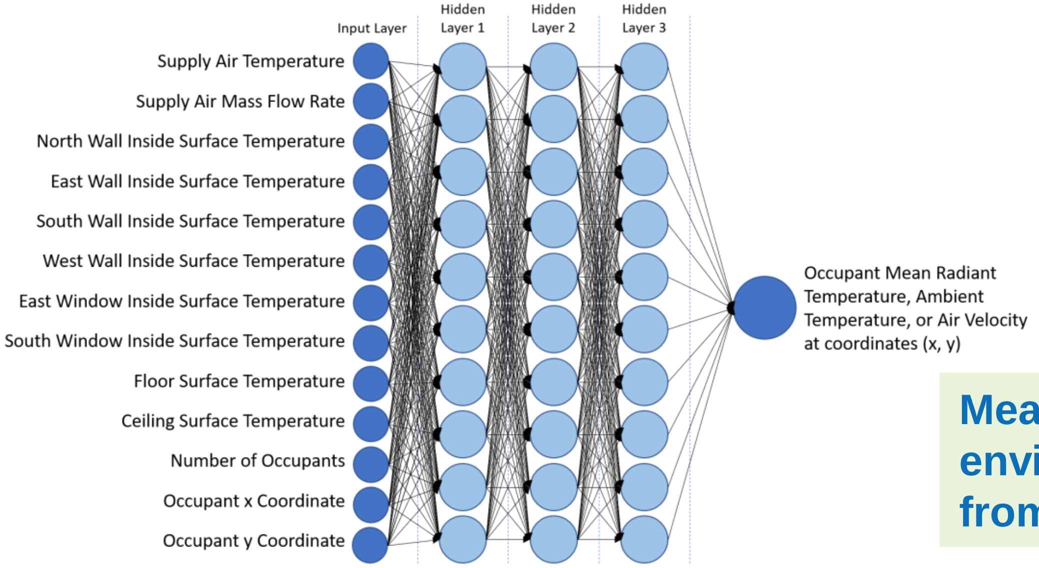


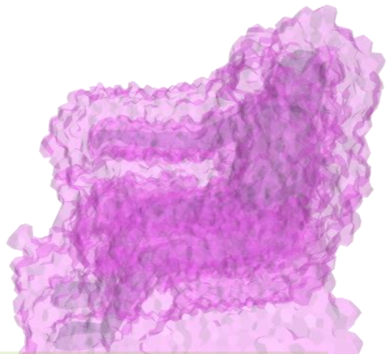
Virtual Building: Airflow Model

- **CFD modeling**
  Simulate occupant local environment at different coordinates
- **Challenges**
  computationally heavy, not suitable for HIL testing
- **Solutions**
  ANN models trained on CFD data [7]





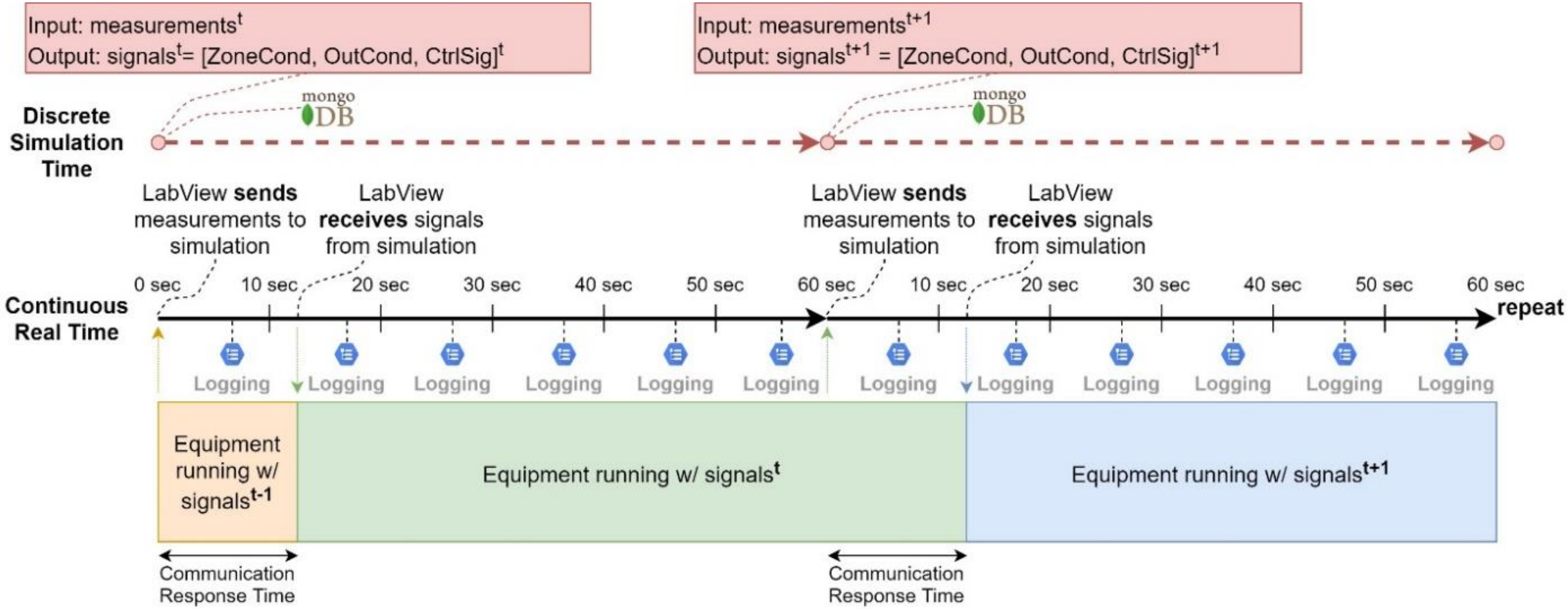




Measured zone environment 4 - 14 cm from occupant's skin

Hardware-Software Integration: Real-time Communication

- 1-min time step
- Communication response time is typically 10-20 seconds for all testing facilities



ZoneCond: Zone air condition; **OutCond**: Outdoor air condition; **CtrlSig**: Control signals

Testing Scenarios: Control Strategies

IBAL

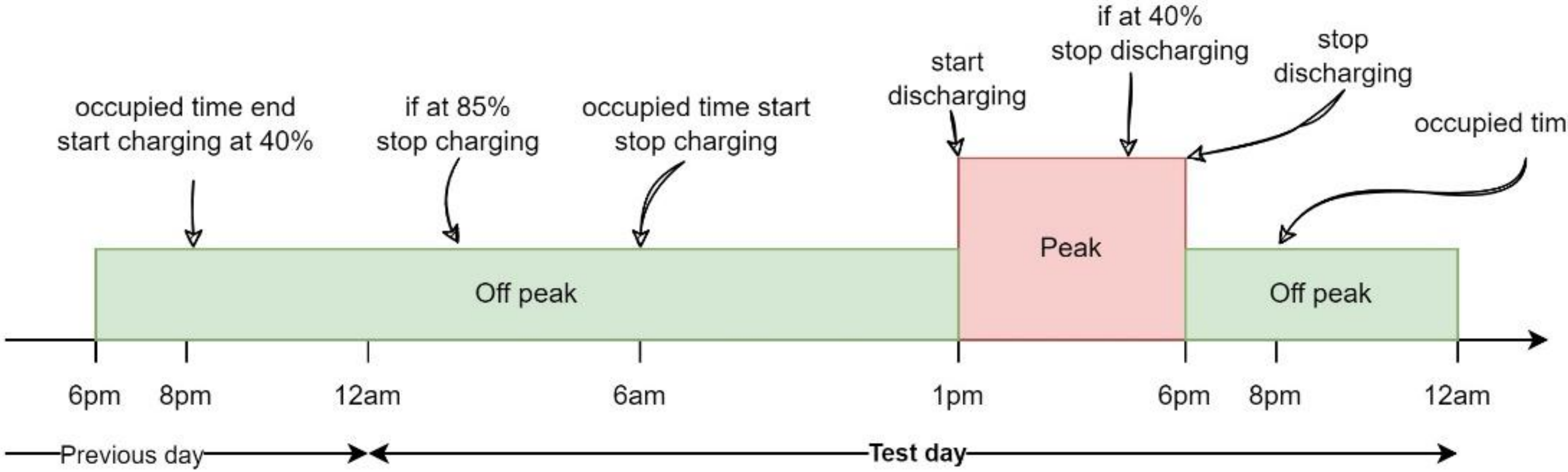
- **Rule-Based Control**
  - Load shedding: global temperature reset
  - Load shifting: global temperature reset or use ice tank, determine the reset schedule through limited real testing
  - ASHRAE 90.1-2004
  - ASHRAE 90.1-2019 and Guideline 36
- **Model Predictive Control**
  - Chiller, ice tank operation scheme
  - System and zone setpoints
  - Optimize energy use, peak demand, or TOU cost
  - Maintain zone temperature within a comfortable range

ASHP/WSHP

- **Rule-Based Control**
  - Load shedding: global temperature reset
  - Load shifting: global temperature reset, determine the reset schedule through simulation
- **Model Predictive Control**
  - Zone temperature setpoint
  - Optimize energy use, peak demand, or TOU cost
  - Maintain zone temperature within a comfortable range

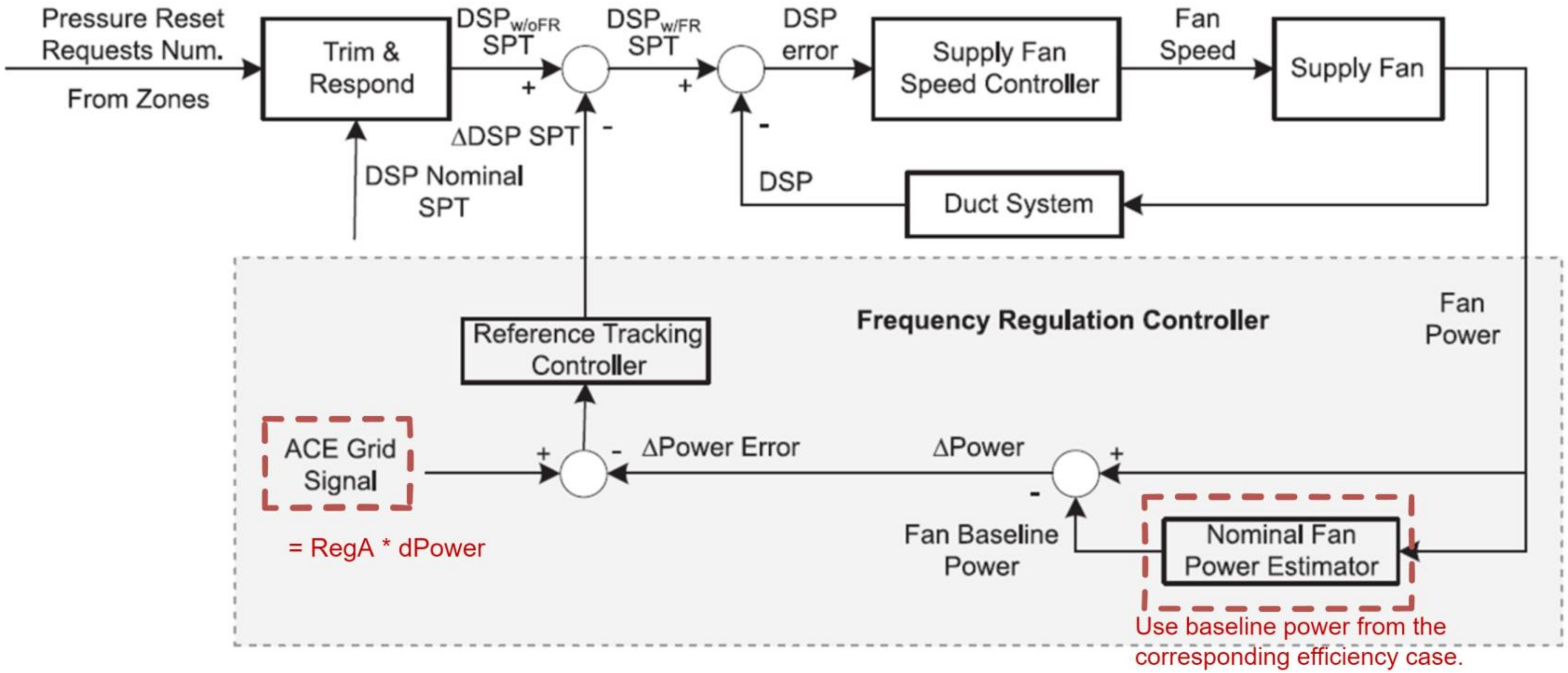
Testing Scenarios: RBC for IBAL Ice Tank

- IBAL ice tank charge/discharge schedule when it is being tested



Testing Scenarios: FR for AHU Fan

- Approach: Local PID
- Static pressure setpoint of IBAL AHU supply fan
- Signals: 40-min RegA test signals provided by PJM [11]

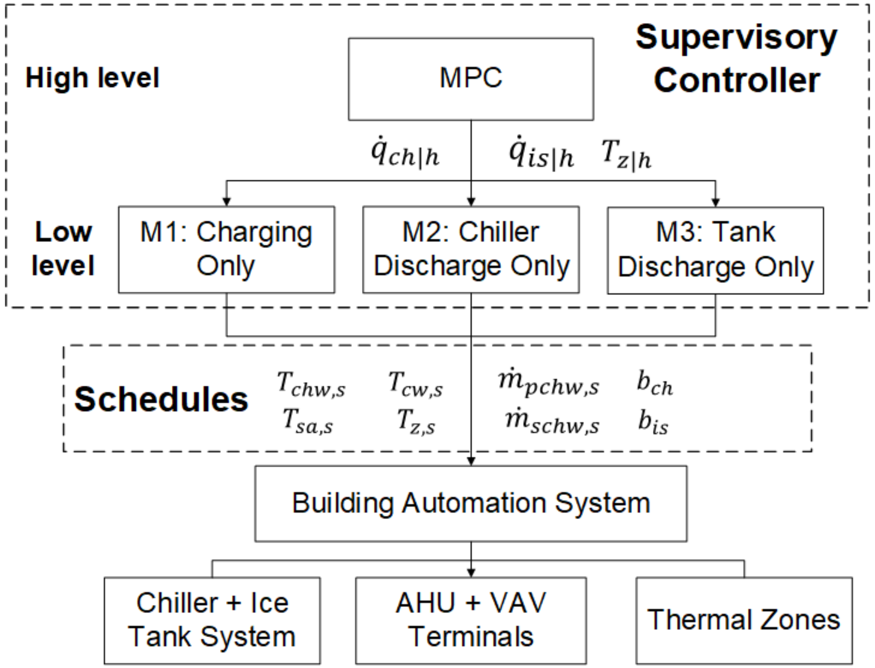


= RegA * dPower

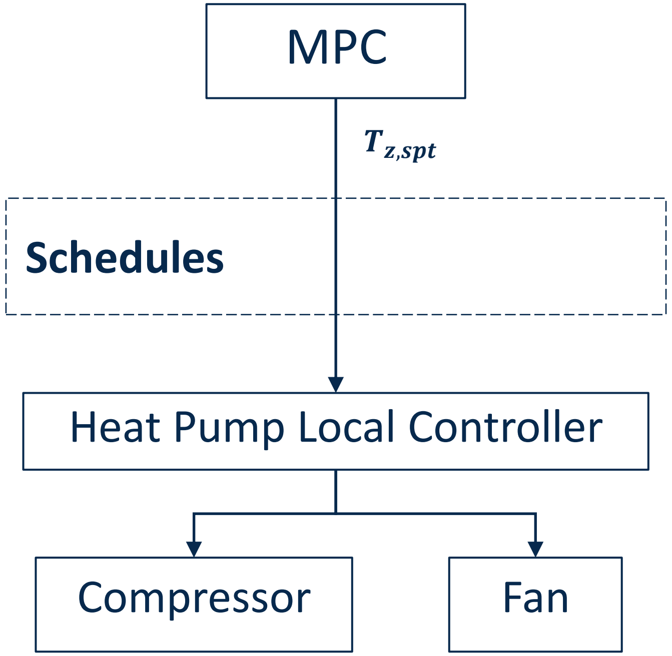
Use baseline power from the corresponding efficiency case.

Testing Scenarios: MPC

- MPC Formulation - Schematics

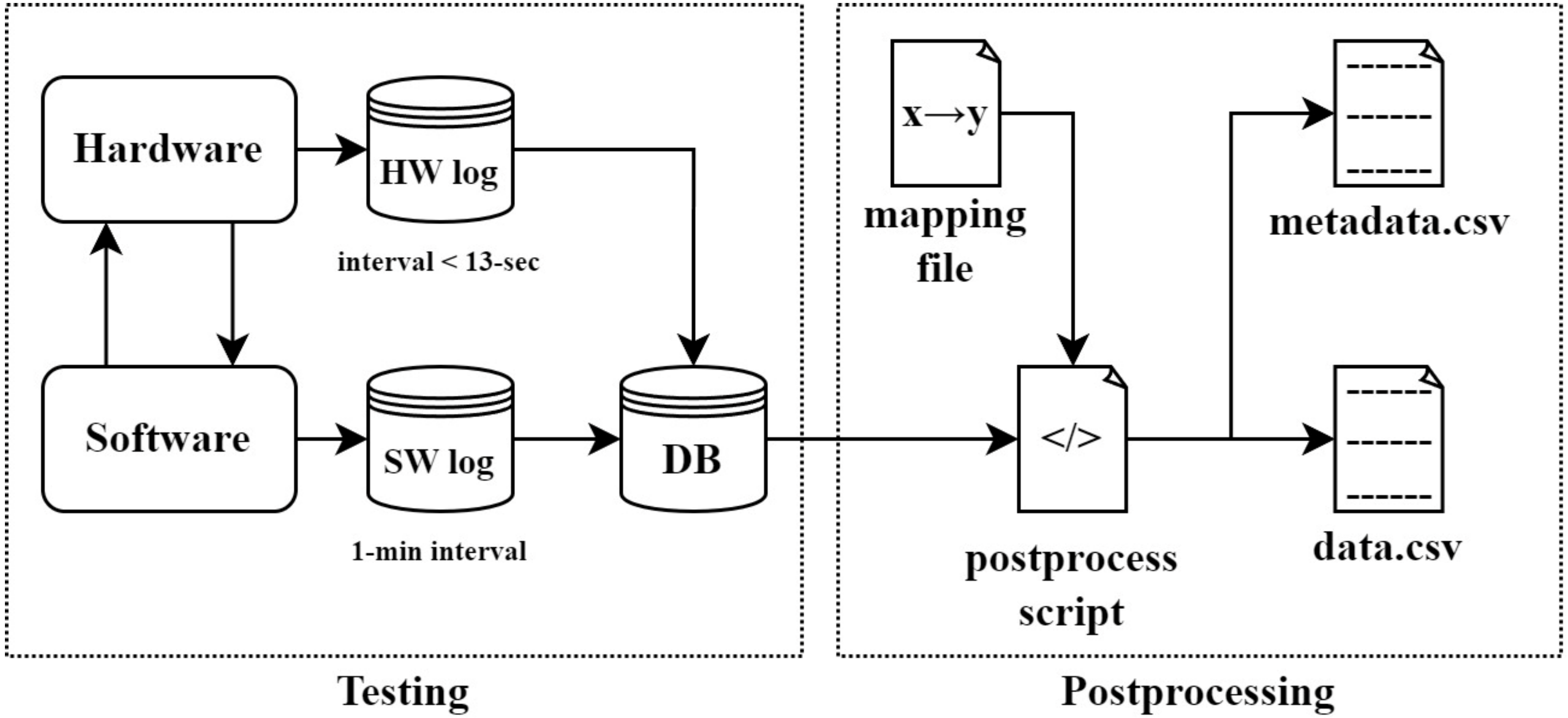


IBAL: Chiller/Ice Tank-AHU-VAV

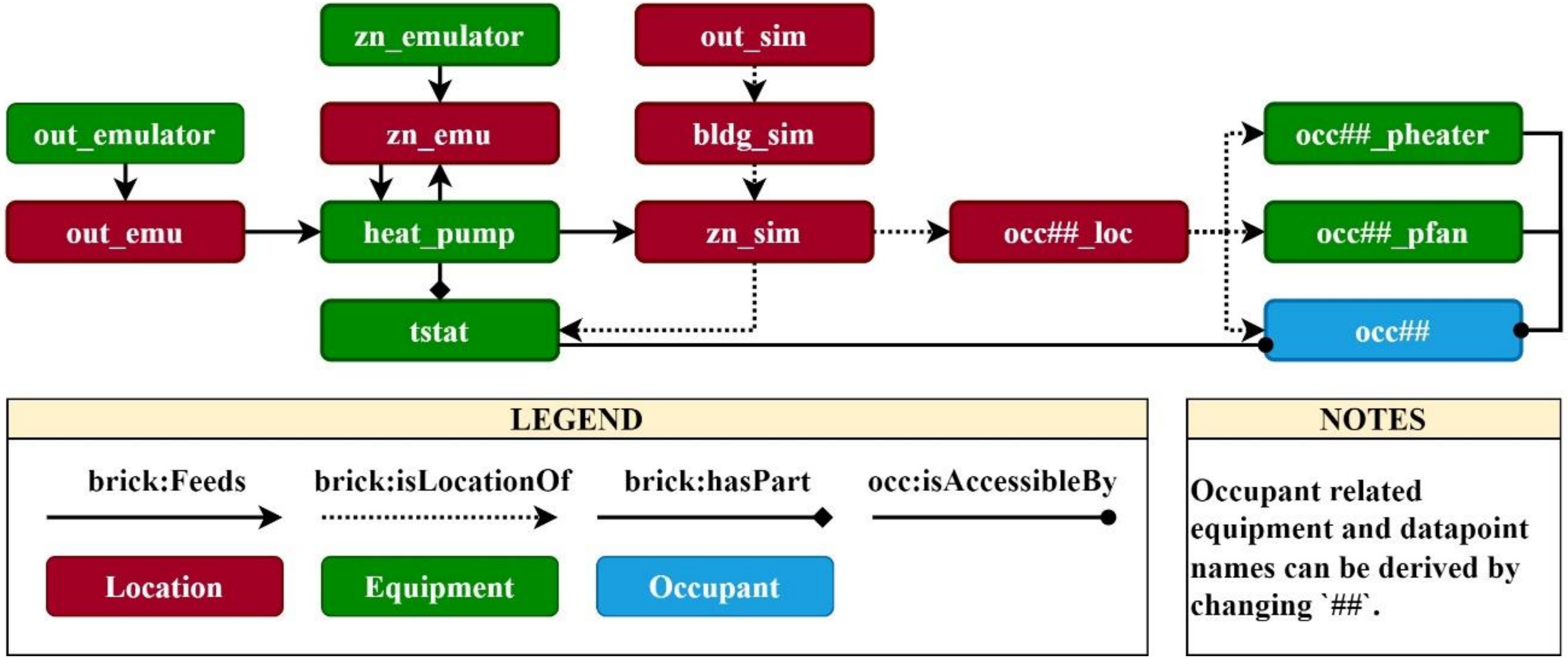


ASHP, WSHP

Method: Postprocess Procedure



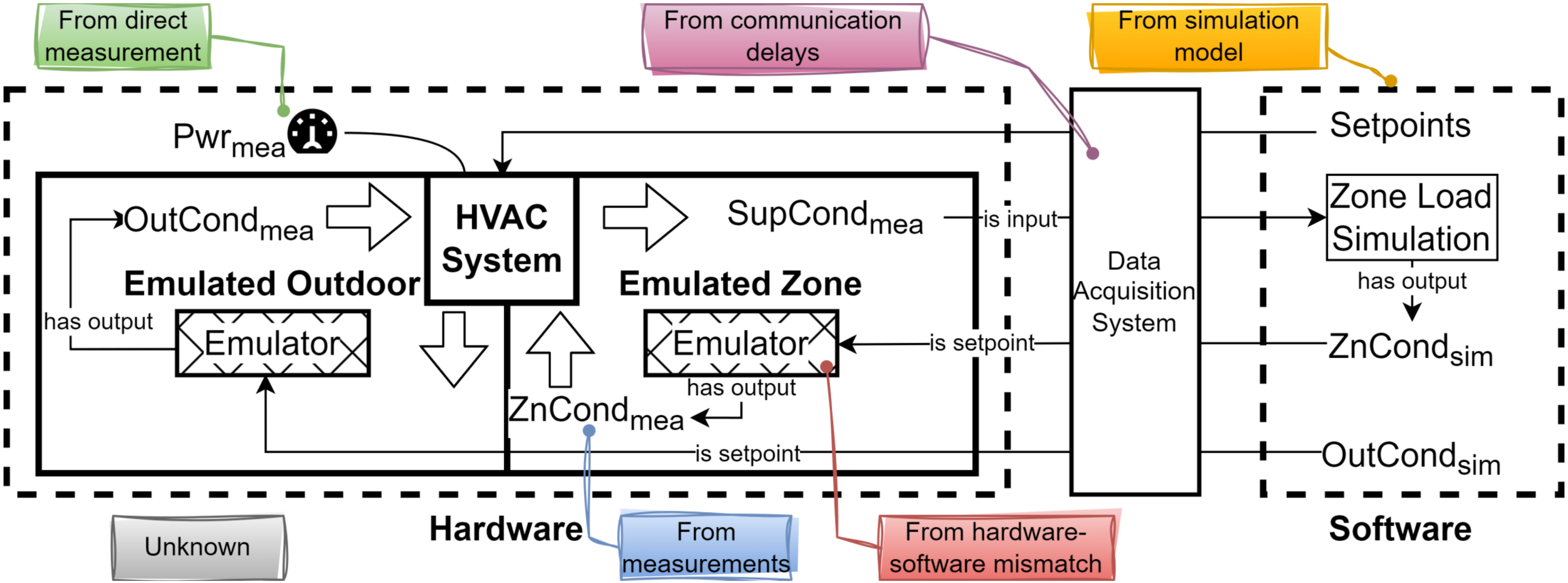
Method: Data Schema



NOTES

Occupant related equipment and datapoint names can be derived by changing `##`.

Technical Validation: Uncertainty Analysis



Technical Validation: Data Quality Control

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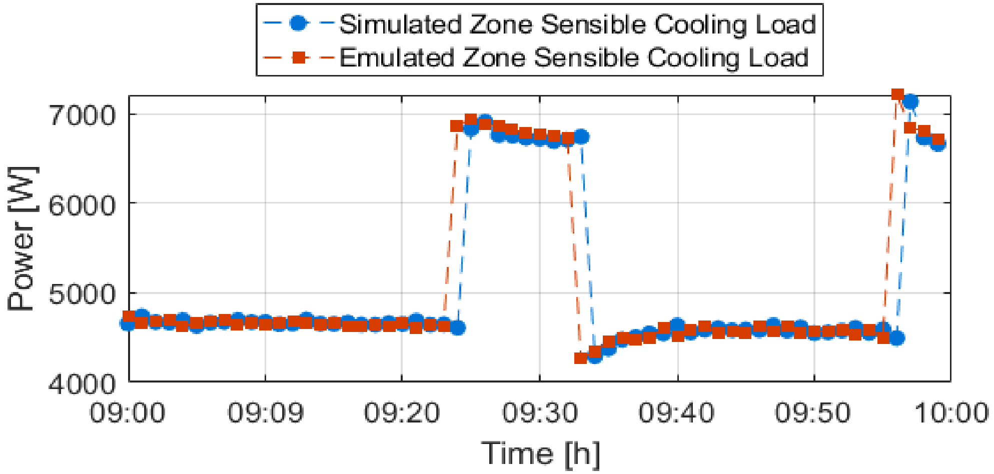
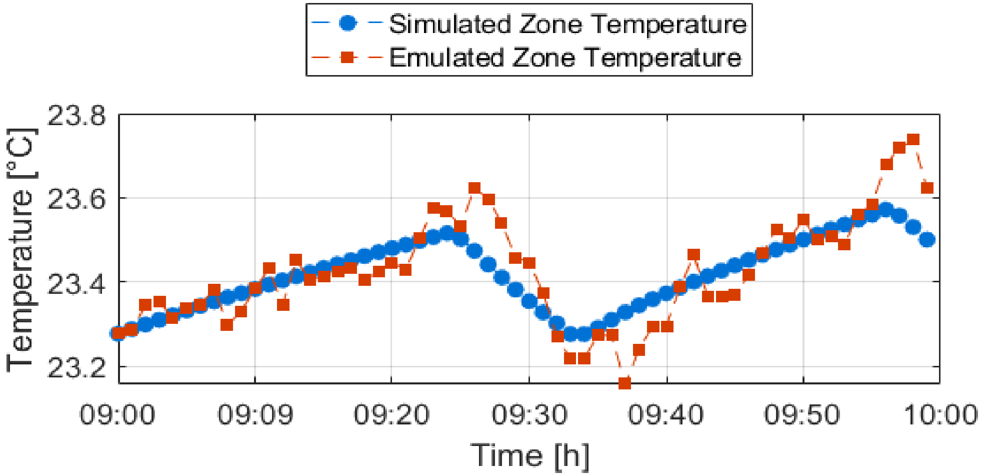
Ensuring integration quality (What to check?)

- Communication delay
- Emulation response time
- Capacities
- Emulation accuracy (i.e., hardware-software mismatch)





Technical Validation: Evaluation of Load Flexibility

KPI [10, 11]	Unit	Need Reference?	Equation
Energy use†	kWh	No	$E = \sum_{1 \leq i \leq N_{ts}} [Q(t_i) \cdot (t_{i+1} - t_i)]$
Average demand†	kW	No	$\overline{Q} = \frac{\sum_{1 \leq i \leq N_{ts}} Q(t_i)}{N_{ts}}$
Flexibility factor†	-	No	$FF = \frac{\sum_{t_i \in nonpeak} Q(t_i) - \sum_{t_i \in peak} Q(t_i)}{\sum_{t_i \in nonpeak} Q(t_i) + \sum_{t_i \in peak} Q(t_i)}$
Time-of-use cost†	$	No	$Cost = \sum_{1 \leq i \leq N_{ts}} [Q(t_i) \cdot (t_{i+1} - t_i) \cdot TOU(t_i)]$
PJM regulation performance score††	-	Yes	$S_c = \frac{1}{3}(S_p + S_{cor} + S_d)$ where $S_p = 1 - \frac{1}{N_{sample}} err(P_g, P_r)$ $S_{cor} = r(P_s, P_r(\tau^*, \tau^* + 5min))$ $S_d = \frac{\tau^* - 5min}{5min}$

t_i: a specific time step,
$Q(t_i)$: power demand at t_i,
N_{ts}: total number of timesteps for a specific time period,
$TOU(t_i)$: TOU price at t_i,
P_g: PJM regulation signal,
P_r : response signal to P_g,
$err(*,*)$: the absolute error between two signals,
N_{sample} : total number of signal samples,
$r(*,*)$: statistical correlation between two signals,
τ^* : time shift when the maximum correlation between two signals occur

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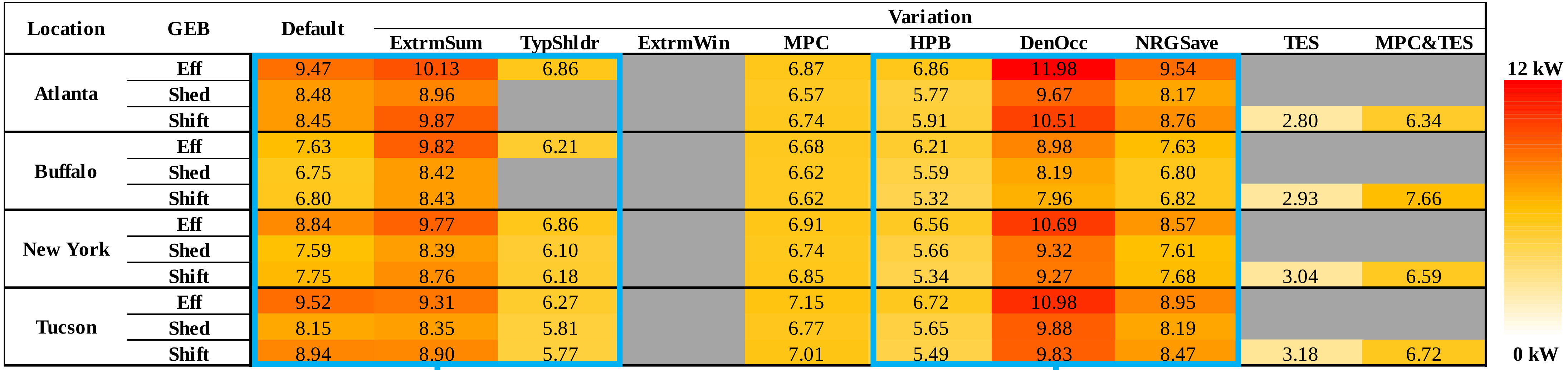
† Li, H., Johra, H., de Andrade Pereira, F., Hong, T., Le Dréau, J., Maturo, A., Wei, M., Liu, Y., Saberi-Derakhtenjani, A., Nagy, Z. and Marszal-Pomianowska, A., 2023. Data-driven key performance indicators and datasets for building energy flexibility: A review and perspectives. Applied Energy, 343, p.121217.

†† PJM, 2022. PJM Manual 12: Balancing Operations. Revision 45.

Evaluation of Load Flexibility

- IBAL (AHU-VAV): Peak demand



Location	GEB	Default	Variation								
			ExtrmSum	TypShldr	ExtrmWin	MPC	HPB	DenOcc	NRGSave	TES	MPC&TES
Atlanta	Eff	9.47	10.13	6.86		6.87	6.86	11.98	9.54		
	Shed	8.48	8.96			6.57	5.77	9.67	8.17		
	Shift	8.45	9.87			6.74	5.91	10.51	8.76	2.80	6.34
Buffalo	Eff	7.63	9.82	6.21		6.68	6.21	8.98	7.63		
	Shed	6.75	8.42			6.62	5.59	8.19	6.80		
	Shift	6.80	8.43			6.62	5.32	7.96	6.82	2.93	7.66
New York	Eff	8.84	9.77	6.86		6.91	6.56	10.69	8.57		
	Shed	7.59	8.39	6.10		6.74	5.66	9.32	7.61		
	Shift	7.75	8.76	6.18		6.85	5.34	9.27	7.68	3.04	6.59
Tucson	Eff	9.52	9.31	6.27		7.15	6.72	10.98	8.95		
	Shed	8.15	8.35	5.81		6.77	5.65	9.88	8.19		
	Shift	8.94	8.90	5.77		7.01	5.49	9.83	8.47	3.18	6.72

Average HVAC Demand during Peak Period

Rule-based Global Temp Reset

- Eff: 78°F T_{cool}
- Shed: relax w/ 80°F T_{cool}
- Shift: precool 3hr w/ 75°F T_{cool} then relax w/ 80°F T_{cool}
- All: T&R SP reset, and OAT-based chilled water temperature reset

Effectiveness

- All cases shown peak demand reduction (3-19%).
- Peak demand reductions are limited by ventilation need.
- Shift case underperforms compared to Shed case, often due to static pressure reset (precool → higher fan static pressure), and lack of thermal mass.

High-Performance Buildings

- HPB has 6-14 % reduced peak demand when compared to non-HPB (Default).
- HPB has 10-19 % reduced peak demand.

Evaluation of Load Flexibility

- IBAL (AHU-VAV): Peak demand

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12 kW

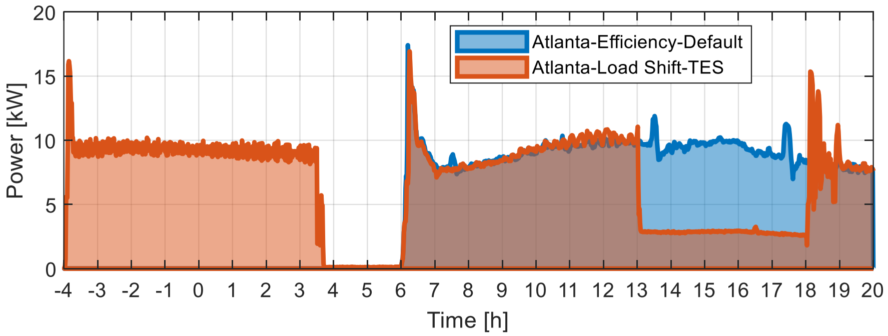
0 kW

Average HVAC Demand during Peak Period

Day-ahead charging. Discharge during peak.

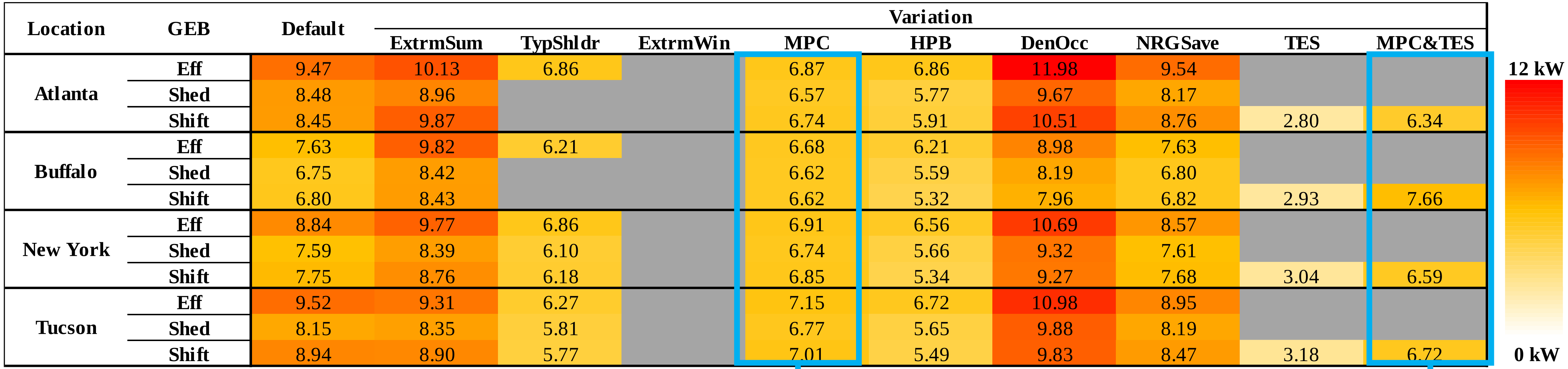
Effectiveness

- 62-70% peak reduction, but overcharge



Evaluation of Load Flexibility

- IBAL (AHU-VAV): Peak demand



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	Shift	8.94	8.90	5.77		7.01	5.49	9.83	8.47	3.18	6.72

Average HVAC Demand during Peak Period

MPC design

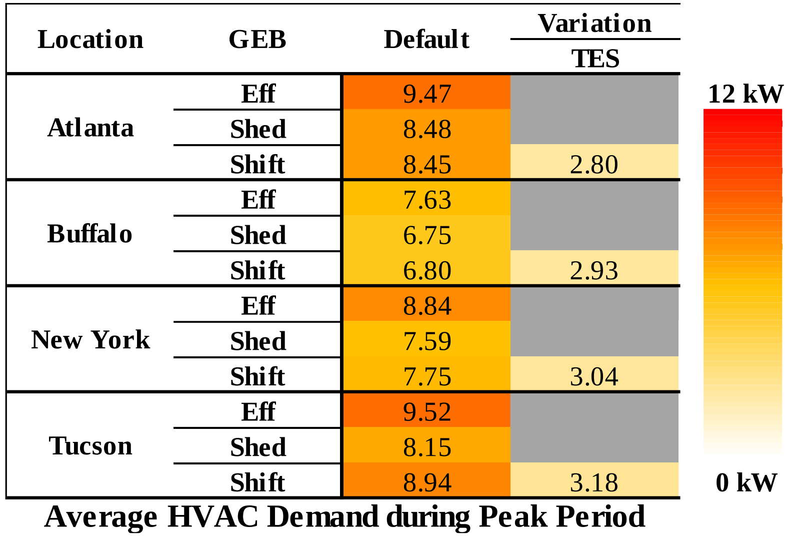
- Optimizes setpoints at an **aggregated** level with limited individual zone and AHU dynamics knowledge.
- Practical for real-time application but may not be the most optimal strategy.

MPC performance

- **MPC**: MPC cases show significant peak demand reductions (12-27%) compared to Default cases. Most peak demand reductions come from reduced ventilation similar to occupancy-based demand ventilation.
- **MPC&TES**: The tested MPC underpredicts the cooling load which results in under utilization of the ice tank.

Evaluation of Load Flexibility

- IBAL (AHU-VAV): Peak demand, flexibility factor, and utility cost



Location	GEB	Default	Variation
			TES
Atlanta	Eff	9.47	
	Shed	8.48	
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	Shed	6.75	
	Shift	6.80	2.93
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	Shed	7.59	
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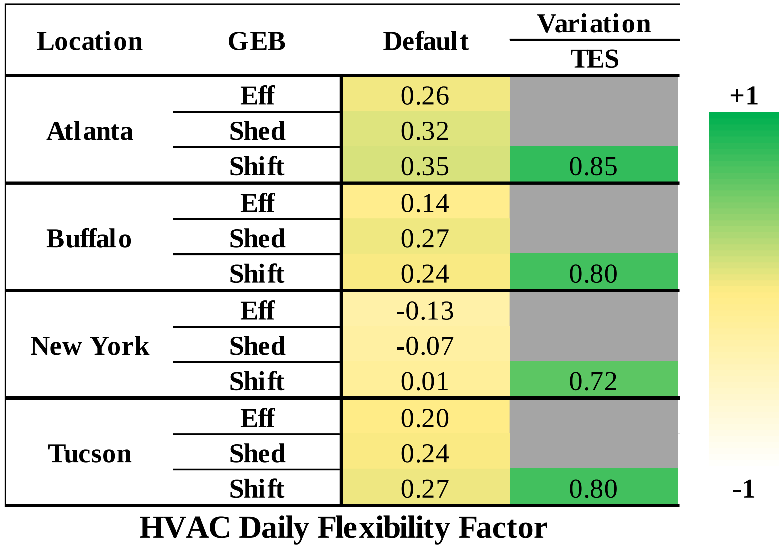
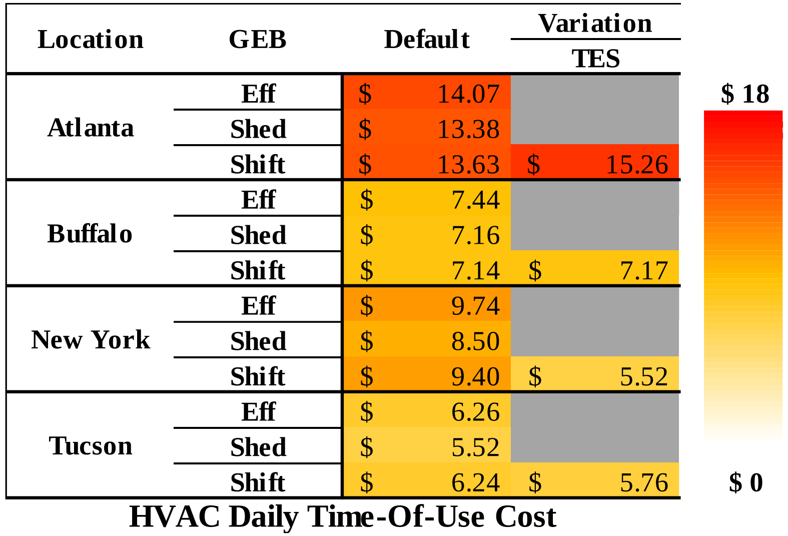
Tucson	Eff	9.52	
	Shed	8.15	
	Shift	8.94	3.18

Average HVAC Demand during Peak Period



Location	GEB	Default	Variation
			TES
Atlanta	Eff	0.26	
	Shed	0.32	
	Shift	0.35	0.85
Buffalo	Eff	0.14	
	Shed	0.27	
	Shift	0.24	0.80
New York	Eff	-0.13	
	Shed	-0.07	
	Shift	0.01	0.72
Tucson	Eff	0.20	
	Shed	0.24	
	Shift	0.27	0.80

HVAC Daily Flexibility Factor



Location	GEB	Default	Variation
			TES
Atlanta	Eff	$ 14.07	
	Shed	$ 13.38	
	Shift	$ 13.63	$ 15.26
Buffalo	Eff	$ 7.44	
	Shed	$ 7.16	
	Shift	$ 7.14	$ 7.17
New York	Eff	$ 9.74	
	Shed	$ 8.50	
	Shift	$ 9.40	$ 5.52
Tucson	Eff	$ 6.26	
	Shed	$ 5.52	
	Shift	$ 6.24	$ 5.76

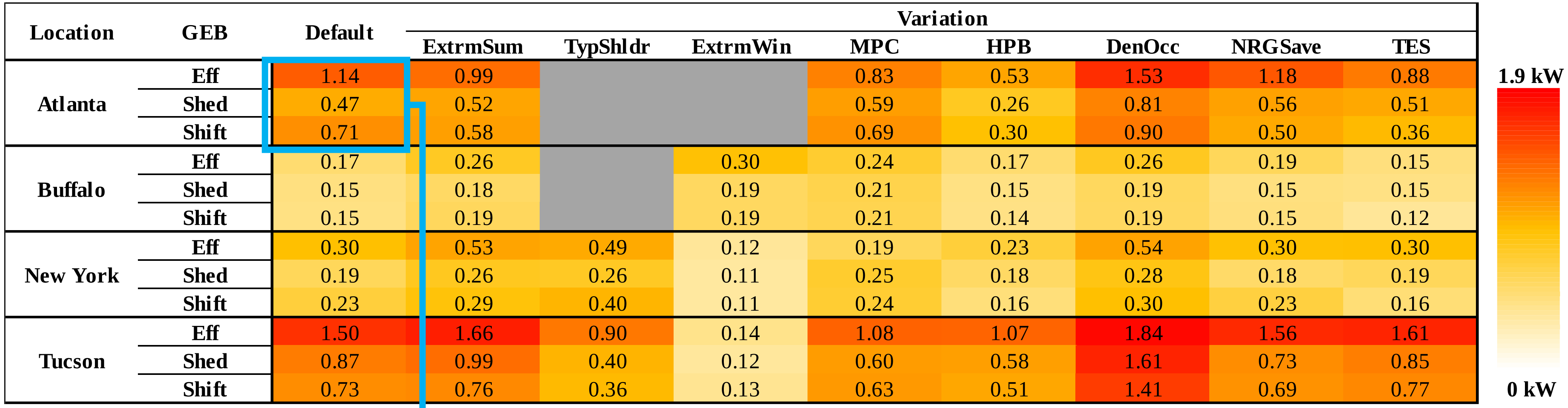
HVAC Daily Time-Of-Use Cost

Insights

- Improved flexibility (high flexibility factor) does not lead to overall utility cost reduction for consumers. -- Pricing structure needs to be carefully designed.
- TOU billed on maximum of the average demand (New York case) results in lower overall utility cost for the TES case when comparing against other cases billed on energy use.

Evaluation of Load Flexibility

- WSHP: Peak demand



Location	GEB	Default	Variation							
			ExtrmSum	TypShldr	ExtrmWin	MPC	HPB	DenOcc	NRGSave	TES
Atlanta	**Eff**	1.14	0.99			0.83	0.53	1.53	1.18	0.88
	Shed	0.47	0.52			0.59	0.26	0.81	0.56	0.51
	Shift	0.71	0.58			0.69	0.30	0.90	0.50	0.36
Buffalo	**Eff**	0.17	0.26		0.30	0.24	0.17	0.26	0.19	0.15
	Shed	0.15	0.18		0.19	0.21	0.15	0.19	0.15	0.15
	Shift	0.15	0.19		0.19	0.21	0.14	0.19	0.15	0.12
New York	**Eff**	0.30	0.53	0.49	0.12	0.19	0.23	0.54	0.30	0.30
	Shed	0.19	0.26	0.26	0.11	0.25	0.18	0.28	0.18	0.19
	Shift	0.23	0.29	0.40	0.11	0.24	0.16	0.30	0.23	0.16
Tucson	**Eff**	1.50	1.66	0.90	0.14	1.08	1.07	1.84	1.56	1.61
	Shed	0.87	0.99	0.40	0.12	0.60	0.58	1.61	0.73	0.85
	Shift	0.73	0.76	0.36	0.13	0.63	0.51	1.41	0.69	0.77

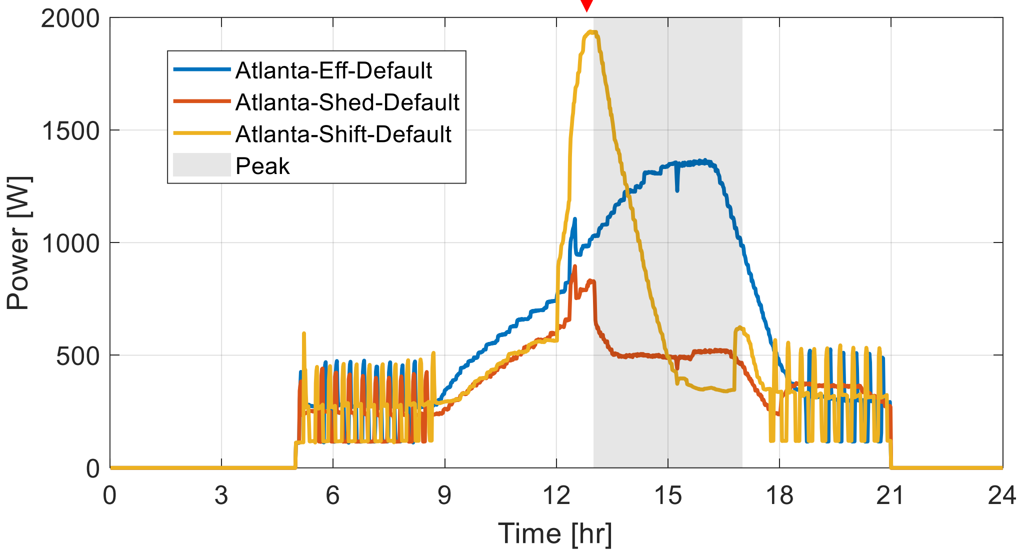
Average HVAC Demand during Peak Period

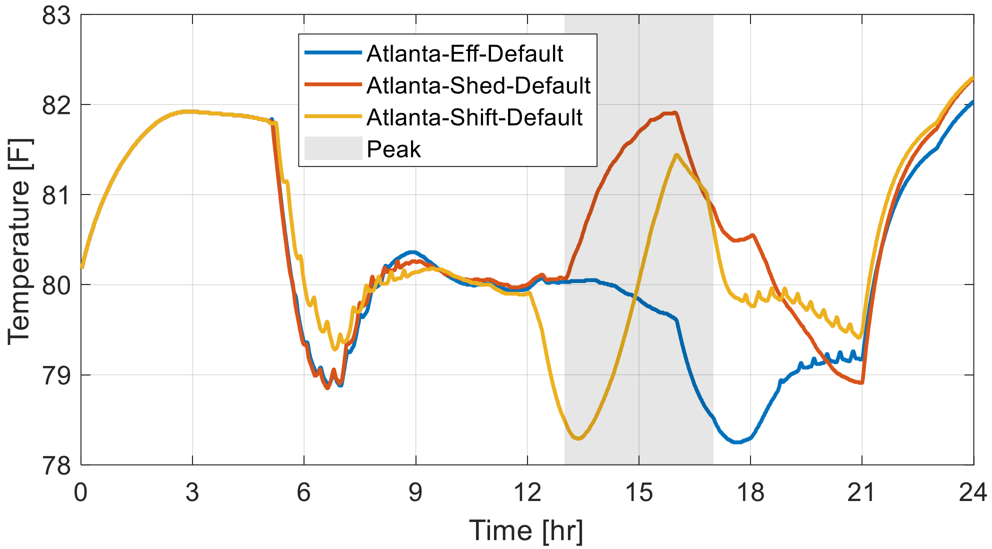
- A Shift case could be much worse than a Shed case

Evaluation of Load Flexibility

- WSHP: Peak demand mitigation

Elevated heat pump power due to precooling

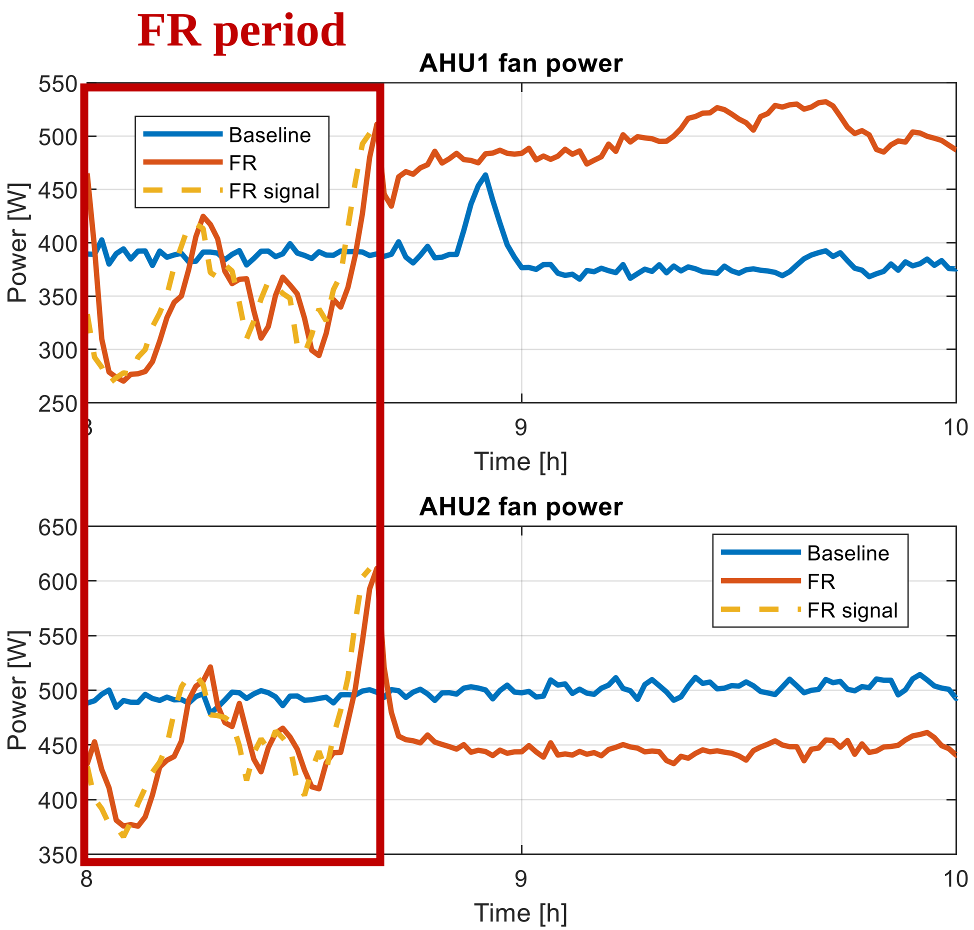




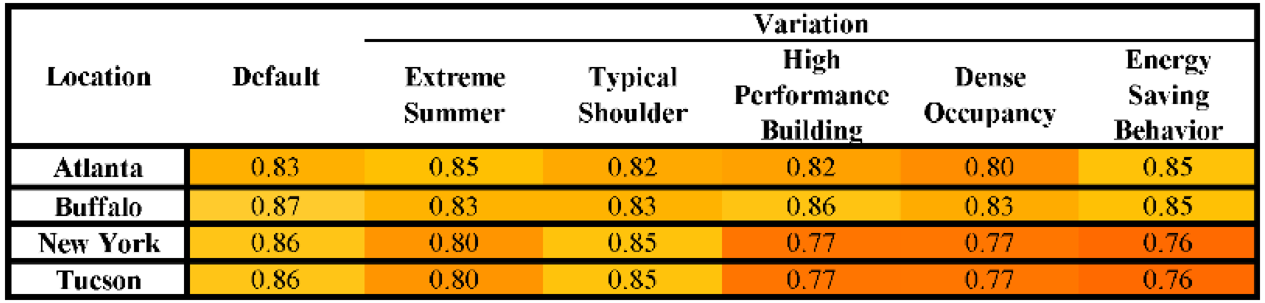
- Overlooked control mechanism delays power reduction after precooling. Compressor speed can not reduce quickly after precooling.

Evaluation of Load Flexibility: Load Modulating

- IBAL AHU fan

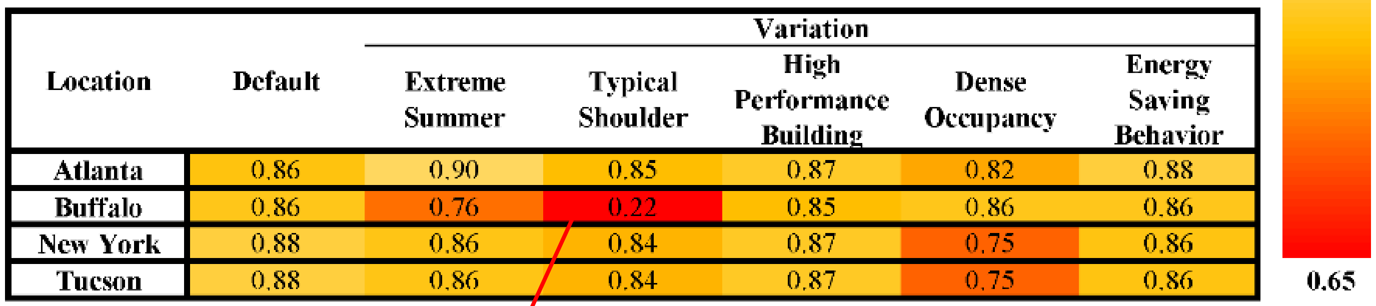


PJM regulation performance score



Location	Default	Variation				
		Extreme Summer	Typical Shoulder	High Performance Building	Dense Occupancy	Energy Saving Behavior
Atlanta	0.83	0.85	0.82	0.82	0.80	0.85
Buffalo	0.87	0.83	0.83	0.86	0.83	0.85
New York	0.86	0.80	0.85	0.77	0.77	0.76
Tucson	0.86	0.80	0.85	0.77	0.77	0.76

(a) AHU1



Location	Default	Variation				
		Extreme Summer	Typical Shoulder	High Performance Building	Dense Occupancy	Energy Saving Behavior
Atlanta	0.86	0.90	0.85	0.87	0.82	0.88
Buffalo	0.86	0.76	0.22	0.85	0.86	0.86
New York	0.88	0.86	0.84	0.87	0.75	0.86
Tucson	0.88	0.86	0.84	0.87	0.75	0.86

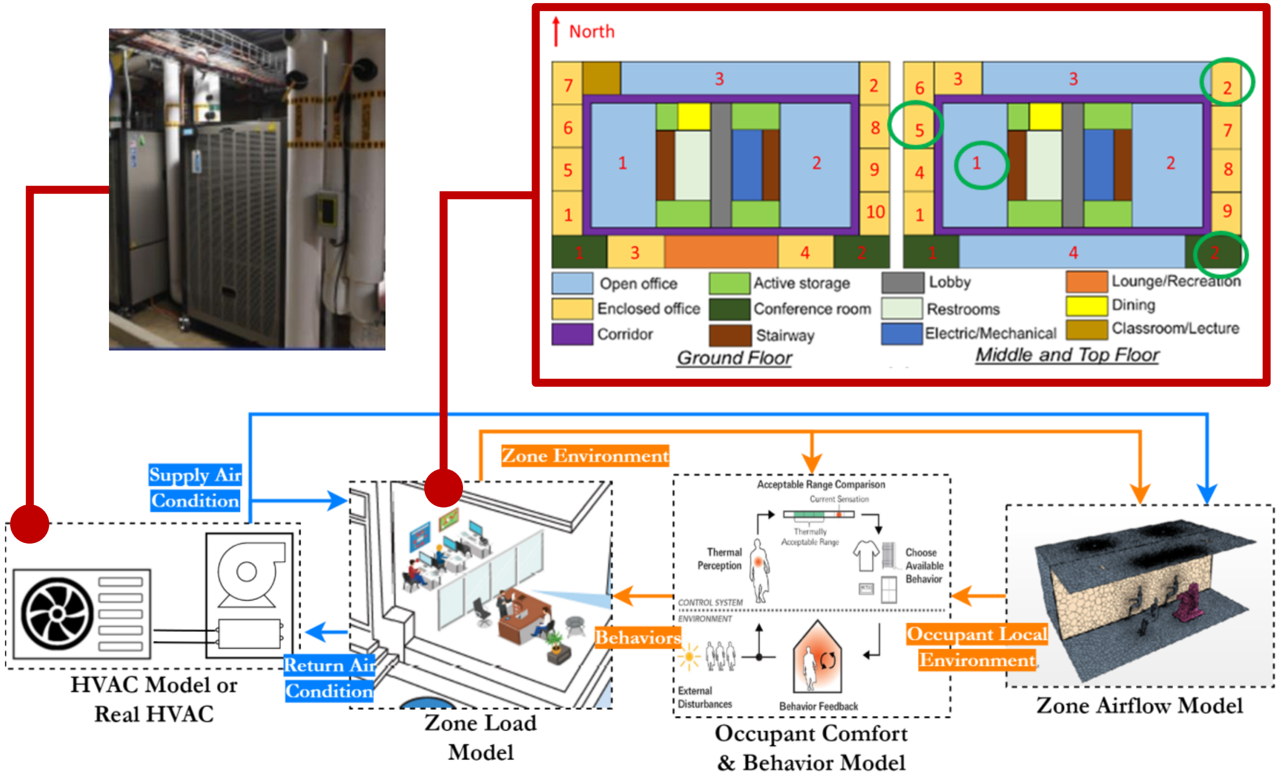
(a) AHU2

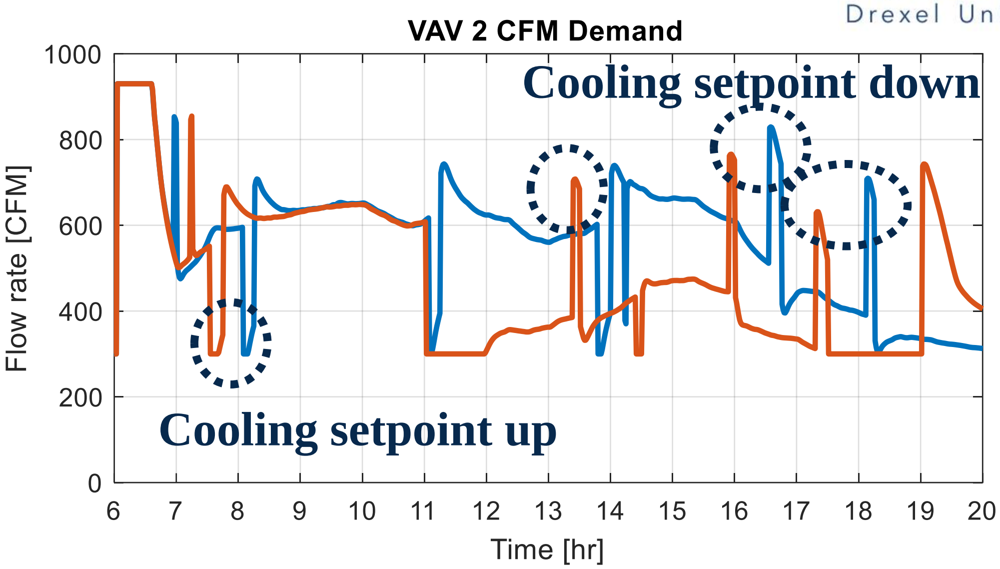
Fan at its minimum speed

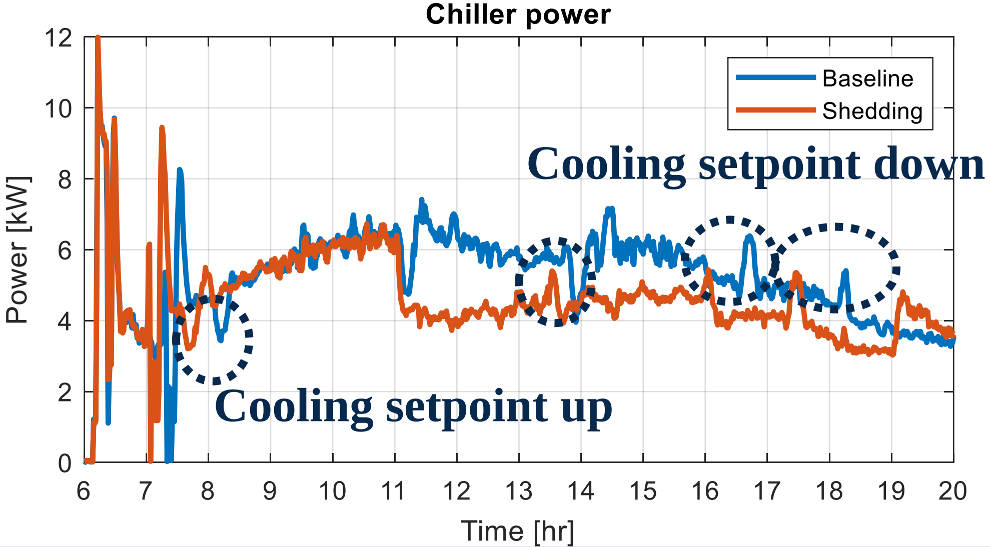
Building Science & Engineering Group
Drexel University

Evaluation of Load Flexibility: Building-Human Interaction

- **Real** chilled water AHU-VAV serving four medium office zones [3, 4, 8]
- Capturing uncertainties from system and occupant behaviors



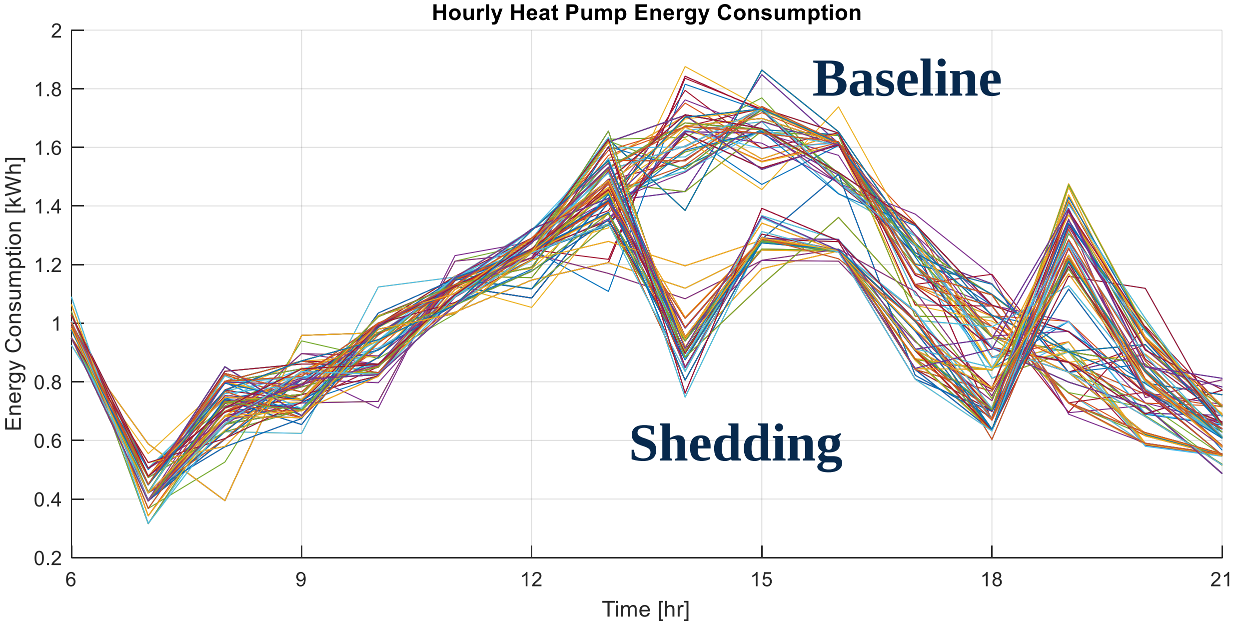


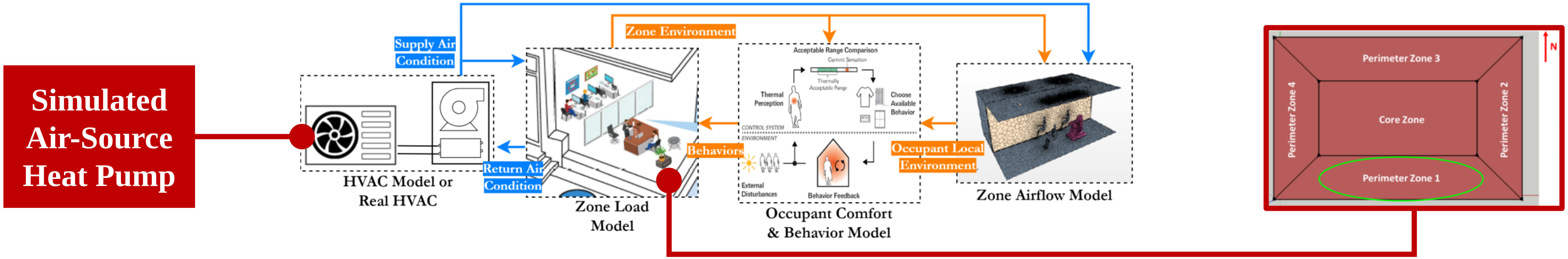


Evaluation of Load Flexibility: Building-Human Interaction

Building Science & Engineering Group
Drexel University

- **Simulated** air-source heat pump serving a small office zone [5, 9]
- Stochastic load profile
- Baseline vs. Load Shedding: 100 simulations each [9]
- Impact of fan/heater usage and setpoint changes on load profile





Evaluation of Load Flexibility: Summary of Insights

Zone Temperature Reset: Effective in reducing peak demand but can cause complex system behavior changes, possibly increasing total system demand.

Advanced Control Strategies: Significantly improve efficiency and reduce peak demand. The quality of MPC affect the performance of DR control.

Thermal Energy Storage: Ice storage reduces peak demand by leveraging off-peak cooling. Cost-effectiveness depends on utility pricing and usage patterns.

Utility Pricing Structure: Significantly affect overall utility cost reduction, even with the same flexibility.

Flexibility Factor: Enhanced flexibility does not always ensure overall utility cost reduction.

Building Thermal Mass: Effectiveness of precooling varies with building thermal mass.

System Responsiveness: Quick system adjustments to setpoint changes are crucial but not always feasible. Understanding system dynamics is vital for effective DR strategy design.

Load Modulating: The AHU fan can be effectively modulated. However, it may change the power trajectory when a static pressure reset is also implemented. FR may fail when fan power is already at its limit.

Building-Human Interaction: Unpredictable occupant behaviors impact energy demand forecasts, necessitating their inclusion in demand flexibility studies.

Discussion

- How can we use the data?

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