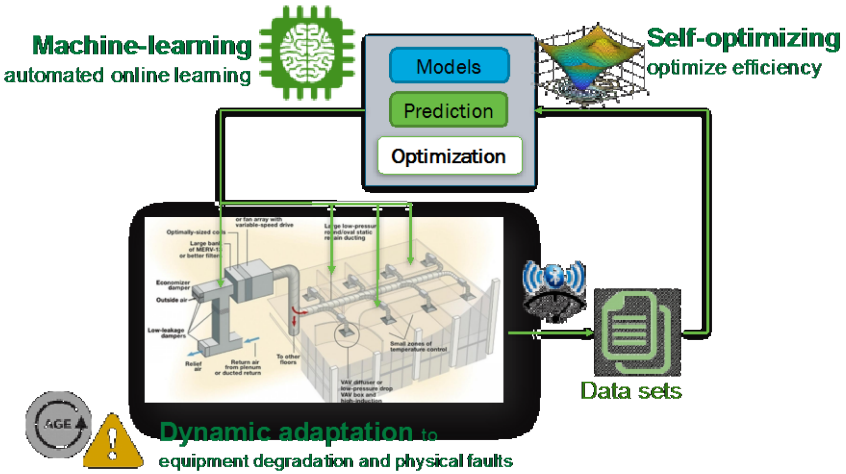
Advancements in Building Controls for Energy Efficiency: Adaptive Control



Pacific Northwest National Laboratory and Oak Ridge National Laboratory
PI: Draguna Vrabie draguna.vrabie@pnnl.gov
Co-PI: Teja Kuruganti kurugantipv@ornl.gov

Project Summary

Timeline:

Start date: 10/01/2016

Planned end date: 09/30/2019

Key Milestones

1. Machine learning methods with simulated data attain <5% RMSE accuracy (met 09/2017)
2. Adaptive supervisory control demonstrated >15% energy consumption reduction (met 01/2018)
3. Online model learning with building data attain <5% RMSE accuracy (due 09/2018)
4. Adaptive control tested at a building site (due 09/2019)

Budget:

Total Project $ (to date):

DOE: $1M

Cost Share: $0

Total Project $:

DOE: $2.1M

Cost Share: $0

Key Partners:

Oak Ridge National Laboratory
Industry Technical Advisory Group

Project Outcomes:

1) Supervisory adaptive control algorithms for commercial buildings with AHU and VAV equipment that can reduce >15% HVAC energy consumption relative to existing ASHRAE 90.1 supervisory baseline.

2) Open-source controls software compatible with the open-source building control platform VOLTTRON™.

3) A high fidelity virtual testbed and baseline control strategies, to serve as a benchmark and to enable the R&D community to develop advanced building controls.

Team

Marina Sofos (Emerging Technologies)
Amy Jiron (Commercial Buildings Integration)

Technical Advisory Group

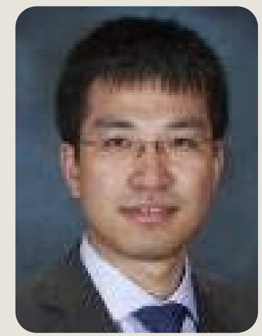

Draguna Vrabie
PNNL


Teja Kuruganti
ORNL


Paul Ehrlich
PNNL


Arnab Bhattacharia
PNNL

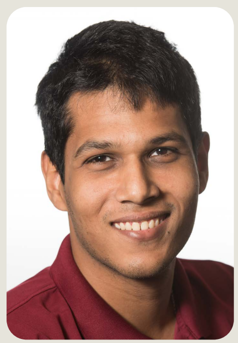

Yan Chen
PNNL


Jin Dong
ORNL


Sen Huang
PNNL


Soumya Kundu
PNNL


Piljae Im
ORNL


Indrasis Chakraborty
PNNL


Robert Lutes
PNNL

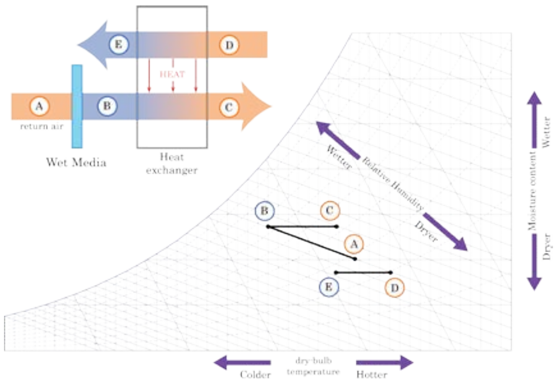

Nikitha Radhakrishnan
PNNL


Thiagarajan Ramachandran
PNNL


Deepak Sivaraman
PNNL

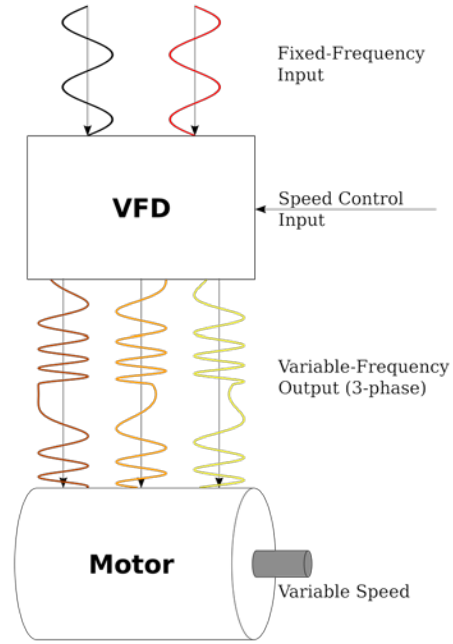
Challenges and Opportunities

Operate >95% of time at partial load



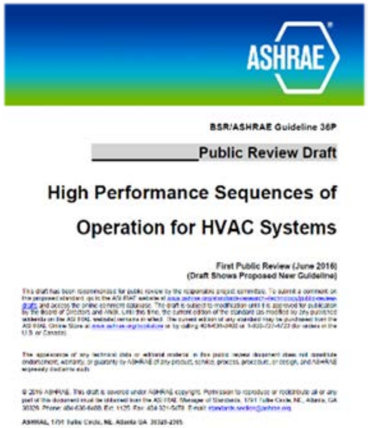
Operation under uncertainty
load variability, equipment aging

Variable speed drives



Daily walk-through
preventative maintenance

Best-of-class sequences
(Guideline 36)



ASHRAE

BSR/ASHRAE Guideline 36P

Public Review Draft

High Performance Sequences of Operation for HVAC Systems

First Public Review (June 2016)
(Draft Shows Proposed New Guideline)

Adjustments based on complaints

Challenges and Opportunities

- Retro-commissioning: cut energy bills by 10-15% [1]
- BAS and control retrofits: up to 30% energy savings [2]

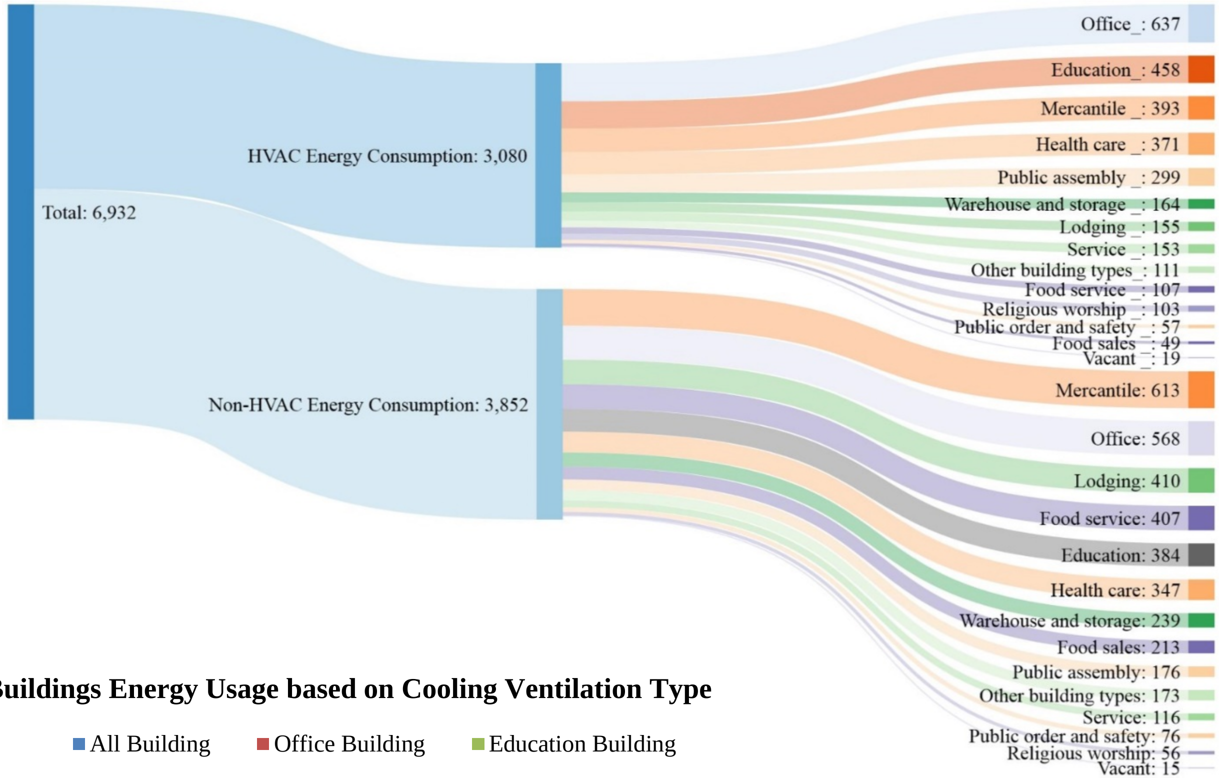
Adoption challenges

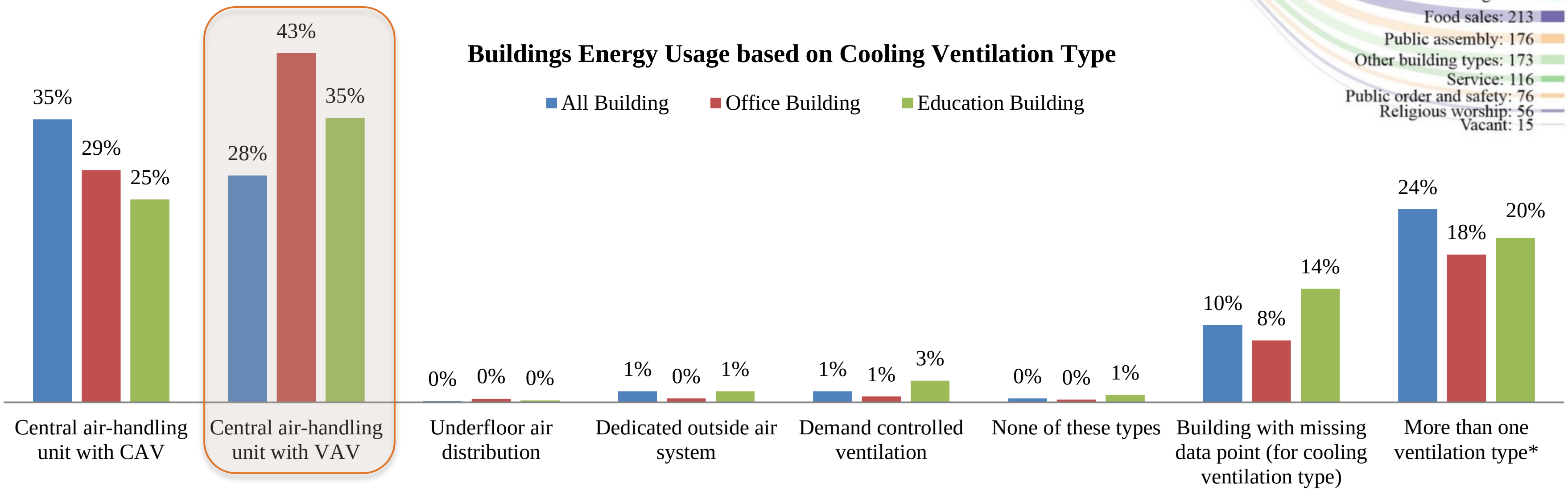
- **Product maturity**: less than 5 years
- **Technology**: proprietary optimization algorithms
- **Energy savings: 10% -40%:** no common baseline
- **Cost**: limited information for full-cycle deployment
- **Deployment and security**: Most products are cloud-based; Security concerns

References
1. Mills, E., H. Friedman, T. Powell, N. Bourassa, D. Claridge, T. Haasl, and M.A. Piette, "The Cost-Effectiveness of Commercial-Buildings Commissioning" (2004), Lawrence Berkeley National Laboratory
2. Fernandez N., S. Katipamula, W. Wang, Y. Xie, M. Zhao, C. Corbin, "Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction," (2017), Pacific Northwest National Laboratory

Background

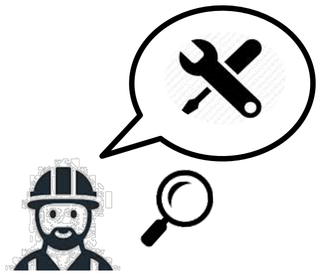
Energy Usage (Trillion Btu) for different types of Commercial Buildings



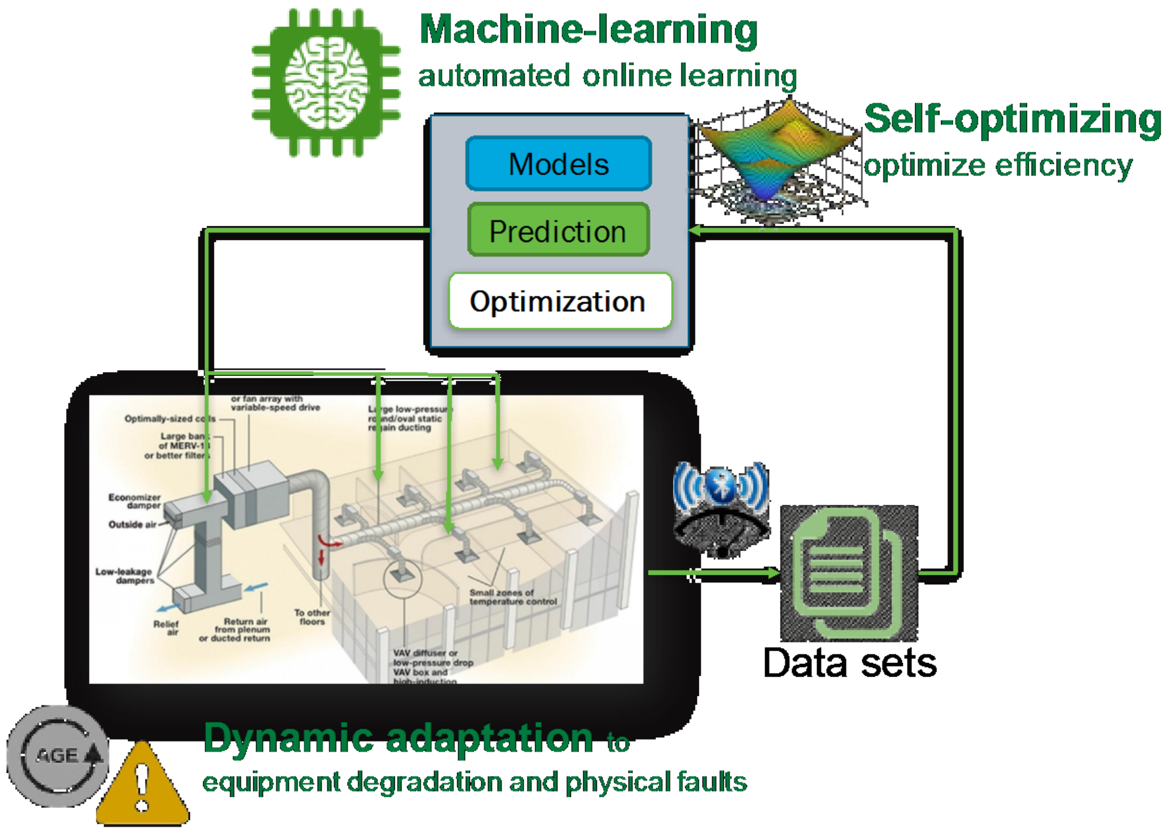


Approach: Adaptive Control

Current state:
Expert engineered rules



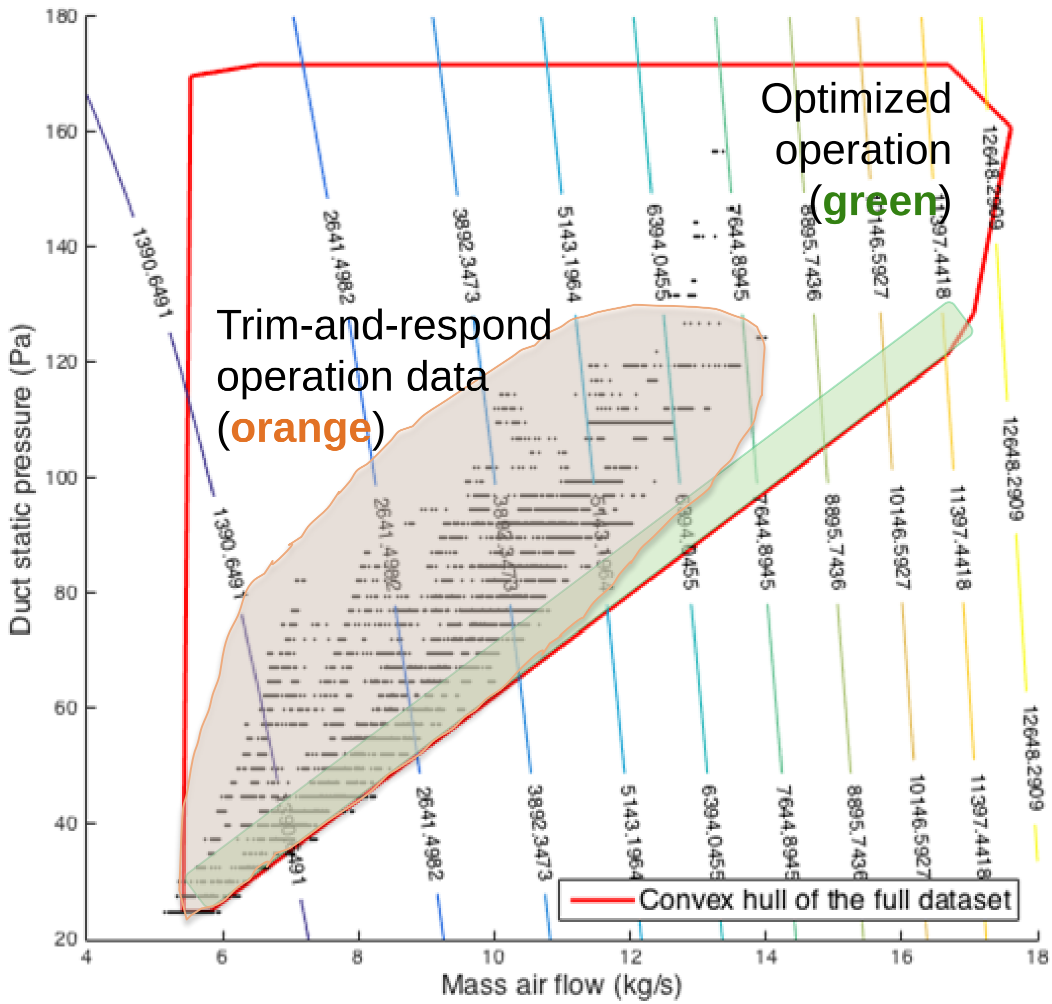
Desired state:



- Machine learning, Model-based predictive control (MPC), Dynamic adaptation
- Test performance in simulation and at building test sites

Approach: Machine Learning

- **Fan power consumption model**

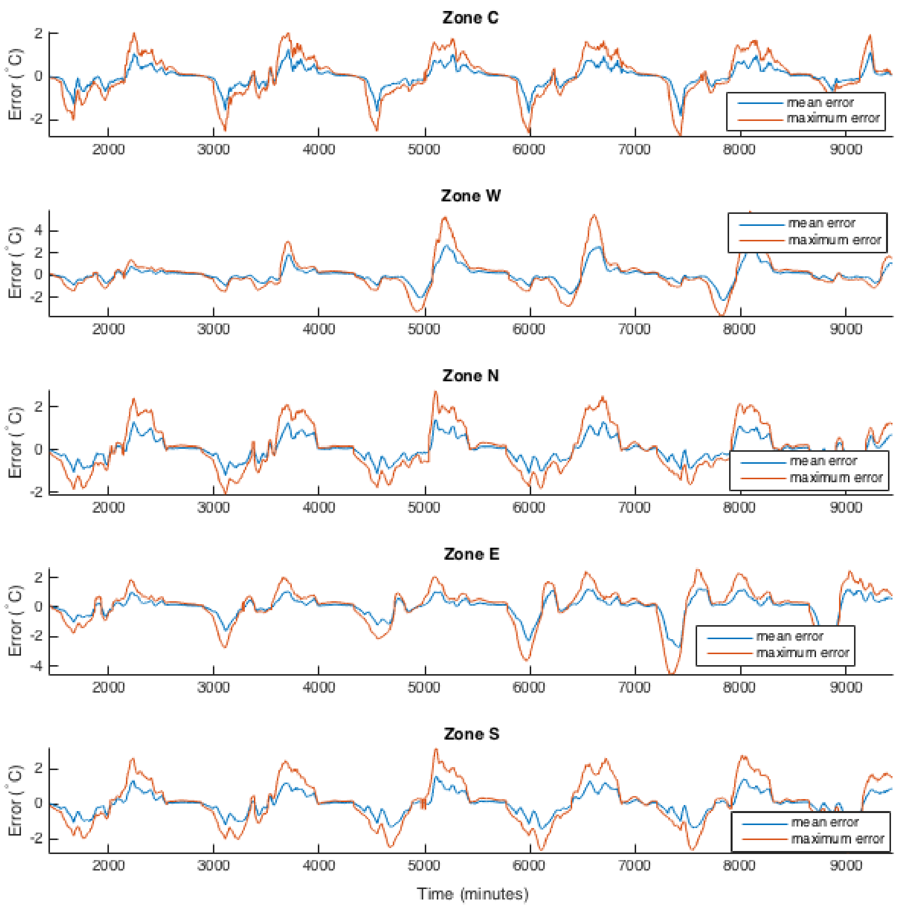


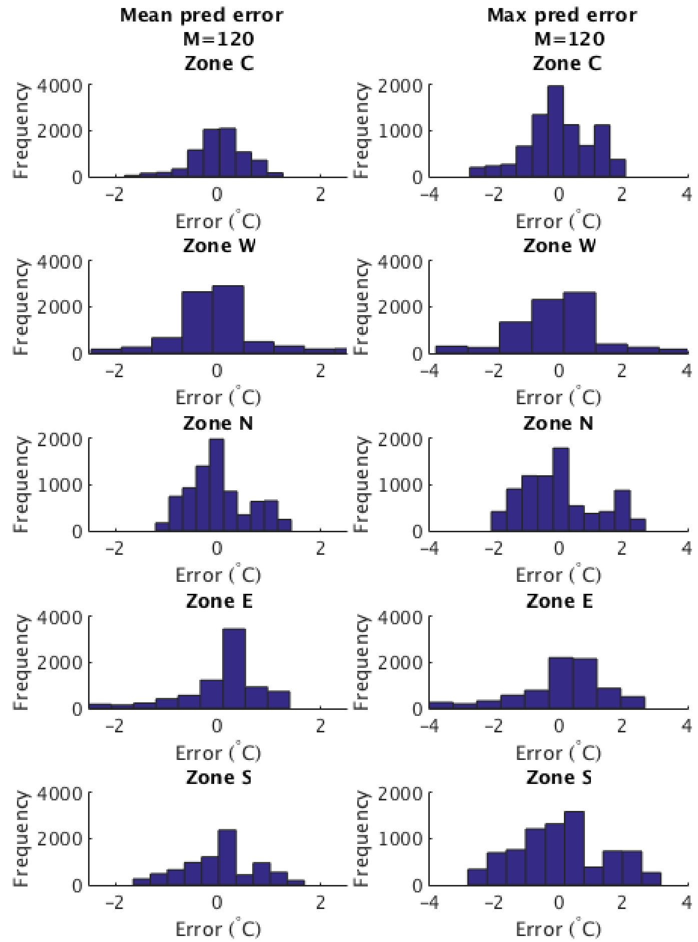
Learning algorithm emphasizes accurate representation of the fan power consumption model at boundary corresponding to optimized operation

Approach: Machine Learning

- **Predictive zone temperature models**

  Performance evaluation on test data - prediction horizon 120 min.





Approach: Dynamic Optimization (MPC)

- **Optimization problem for one Air Handling Unit serving *N* zones**

Minimize heating and cooling capacity over prediction horizon while satisfying comfort constraints

$$z(\Theta) = \min_{x^1,\ldots,x^K} \left\{ \sum_{t\in\mathcal{T}} \left(\eta_f P_f^t + \eta_h P_h^t + \eta_c P_c^t\right) + \lambda v^2 \right\},$$

$$\text{s.t.}\quad T_n^t = \sum_{j=1}^{q} \widehat{\alpha}_n^j T_n^{t-j} + \widehat{\beta}_n m_n^t \left(T_{s,n}^t - T_n^t\right) + \widehat{\gamma}_n T_o^t + Q_n^t,$$

$$P_f^t = \theta_0 + \theta_1 \sum_{n\in\mathcal{N}} m_n^t + \theta_2 \left(\sum_{n\in\mathcal{N}} m_n^t\right)^2 + \theta_3 p^t,$$

$$\left(p^t, \sum_{n\in\mathcal{N}} m_n^t\right) \in \widehat{\mathcal{C}},$$

$$P_h^t = \nu_h c_p \sum_{n\in\mathcal{N}} m_n^t \left(T_i^t - T_m^t\right) + c_p \sum_{n\in\mathcal{N}} \nu_n m_n^t \left(T_{s,n}^t - T_s^t\right)$$

$$P_c^t = \nu_c c_p \sum_{n\in\mathcal{N}} m_n^t \left(T_i^t - T_s^t\right),$$

$$T_r^t = \sum_{n\in\mathcal{N}} m_n^t T_n^t \Big/ \sum_{n\in\mathcal{N}} m_n^t,$$

$$T_m^t = d^t T_o^t + (1-d^t) T_r^t,$$

$$T_n^t \geq T_n^\ell - v,$$

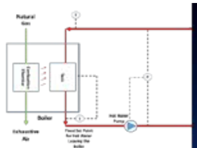
$$T_n^t \leq T_n^u + v,$$

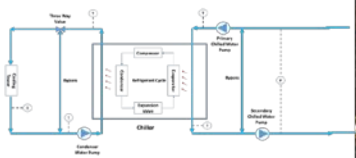
Constraints on decision variables

Variable	Notation	Units	Range
Supply-air temperature	T_s^t	°C	[12.8, 70.0]
Discharge-air temperature in zone n	$T_{s,n}^t$	°C	$[T_s^t, 70.0]$
Mixed-air temperature	T_m^t	°C	$[\min\{T_o^t, T_r^t\}, \max\{T_o^t, T_r^t\}]^*$
Mass-flow rate in zone 1	m_1^t	kg/s	[1.31, 13.10]
Mass-flow rate in zone 2	m_2^t	kg/s	[0.27, 2.70]
Mass-flow rate in zone 3	m_3^t	kg/s	[0.18, 1.79]
Mass-flow rate in zone 4	m_4^t	kg/s	[0.23, 2.28]
Mass-flow rate in zone 5	m_5^t	kg/s	[0.21, 2.08]
Static pressure	p^t	Pa	[24.88, 171.70]

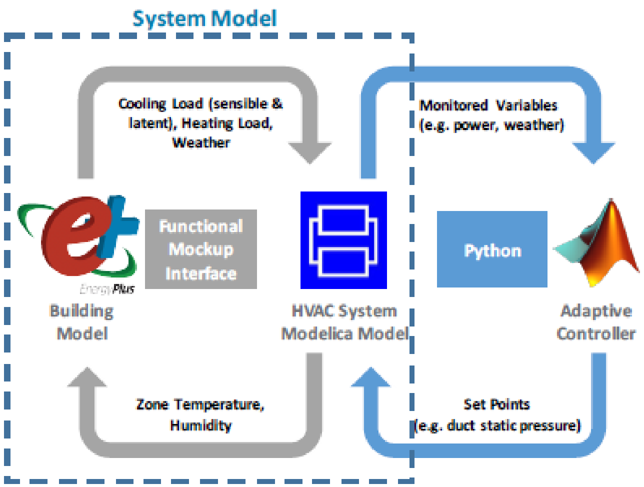
Approach: Testing

Virtual Testbed: high-fidelity simulation


Hot Water System


Chilled Water System


Large Office Building



Building Testbeds


ORNL: Flexible Research Platform (FRP)


PNNL: System Engineering Building (SEB)

Impact

- Contribute to 30% savings for HVAC by 2030 in the commercial sector through advanced controls and $0.12/square feet cost target

Objectives	Activities	Outputs	Short-Term	Mid-Term	Long-Term
Improve cost & performance of fault-tolerant integrated control systems with automated and continuous commissioning	Control design & software for automated learning and optimization under uncertainty	Predictive adaptive controls that optimize building HVAC operations	Vendors offer sensors & control systems that optimize building operations	Vendors offer easy- to-use control systems Owners & operators install control systems that maximize performance	Controls widely used to enhance building performance, Demand response, lower costs

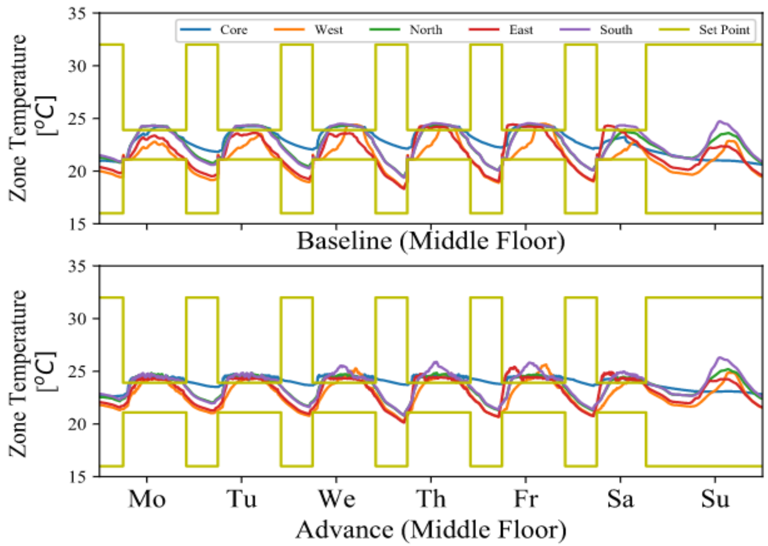
Current project → (Objectives, Activities, Outputs)

Expected impact → (Short-Term, Mid-Term, Long-Term)

- Meet cost & performance targets to enable optimized building performance
- Mitigate the technical challenges to facilitate market transition

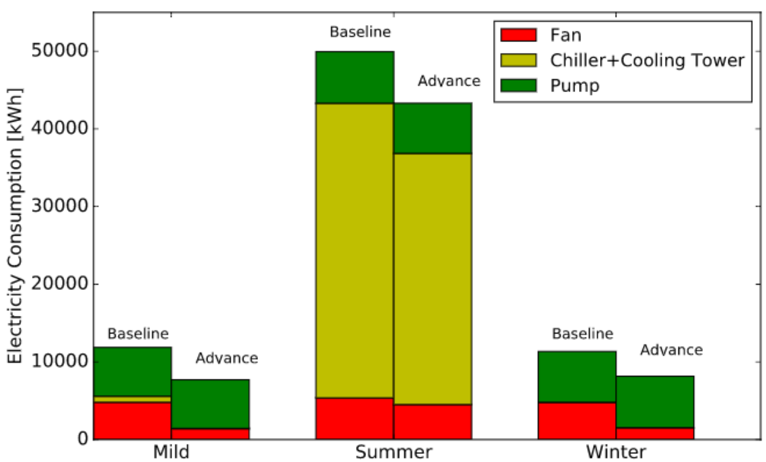
Progress: Virtual Testbed

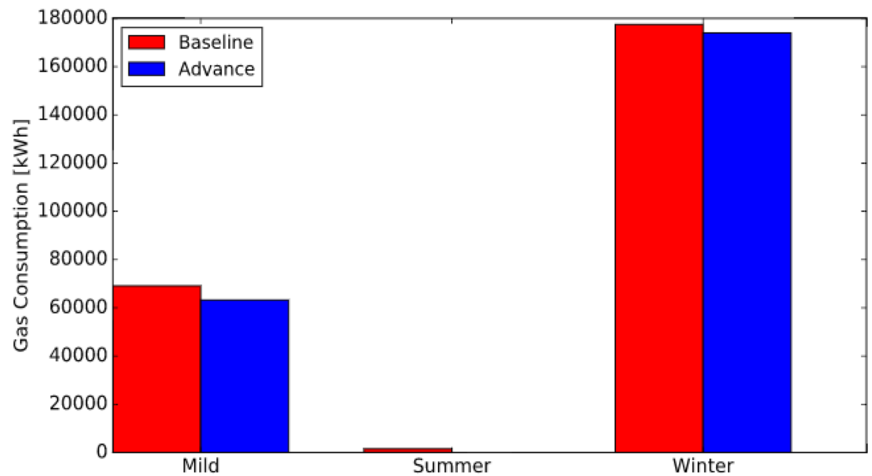
- Baseline controls implemented



Baseline: modified based on ASHRAE 90.1-1989 and 1999

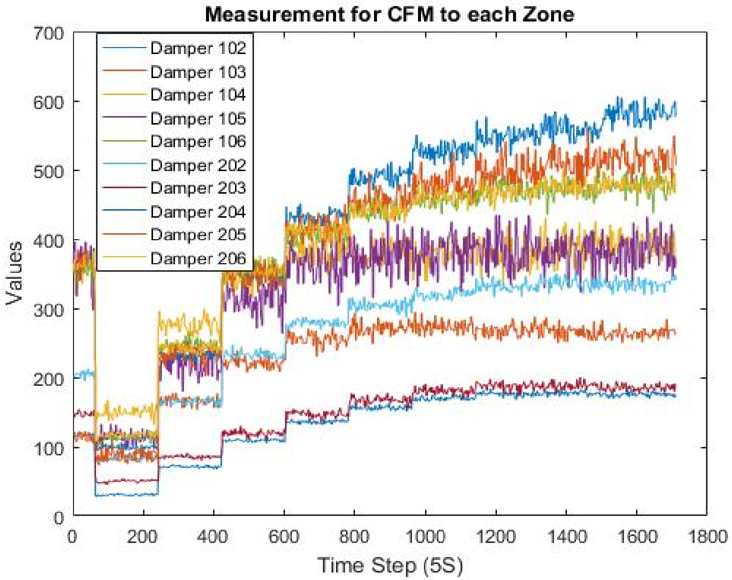
Advanced: modified based on ASHRAE 90.1-2013

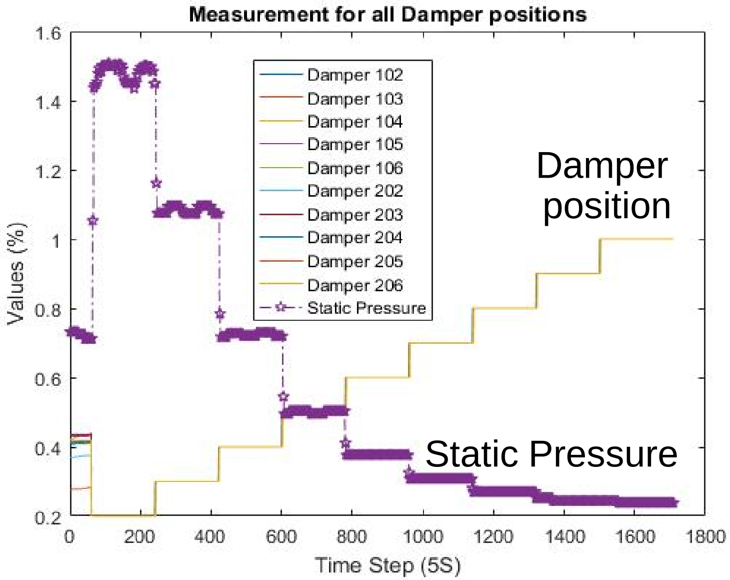


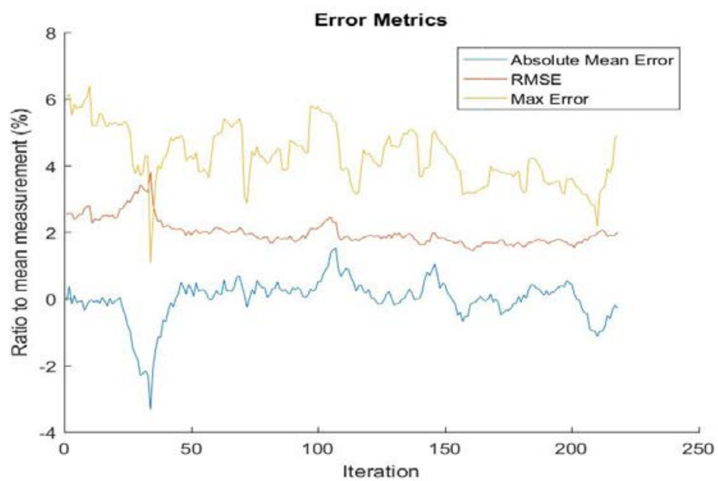


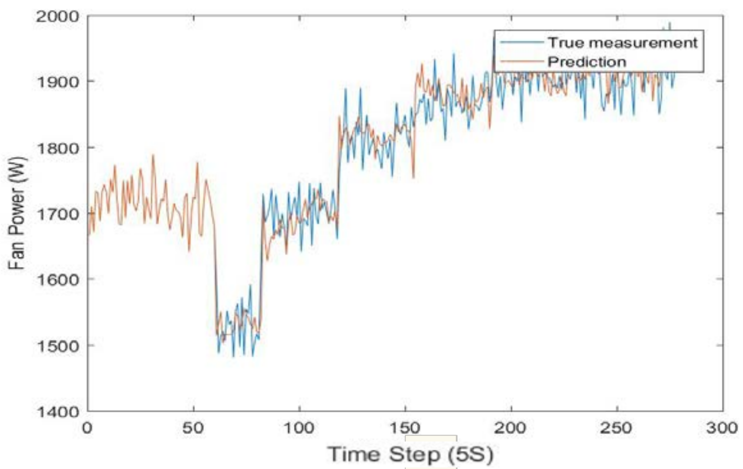
Progress: Online Learning Methods

- Tested with FRP data (**10 zones**, 2 floors) 3/29/2018



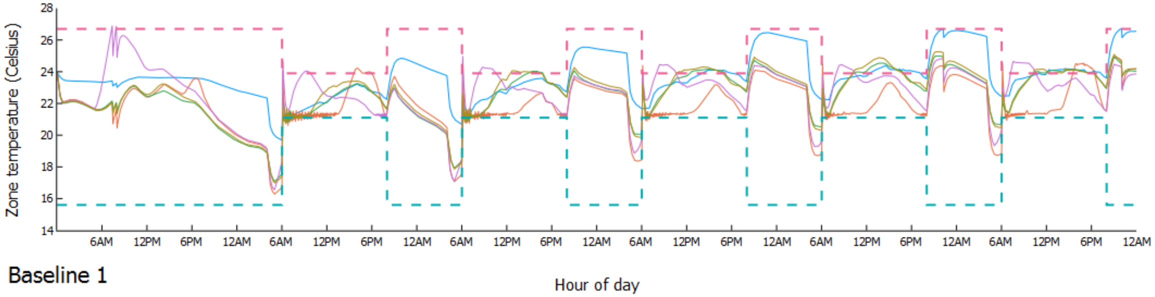




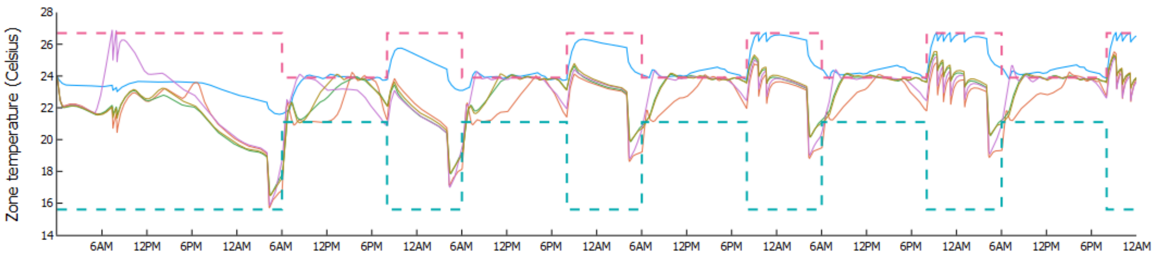


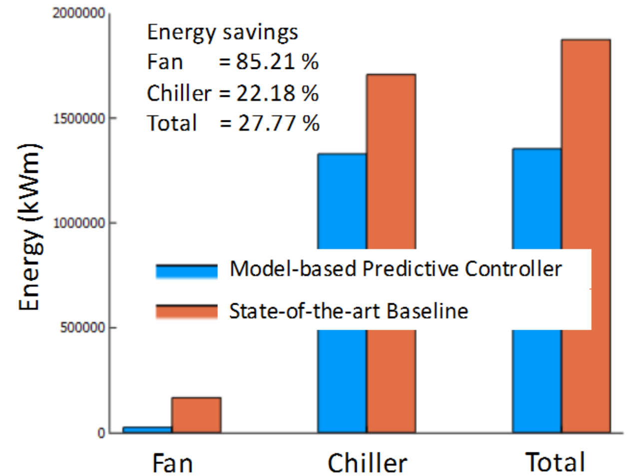
Progress: Control Evaluated in Simulation

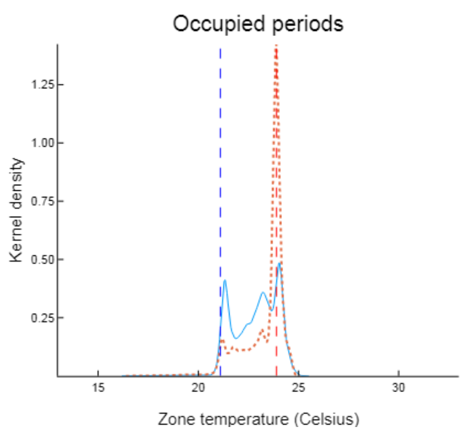
- Model predictive control
  sample simulation result (prediction horizon 60min, summer week)

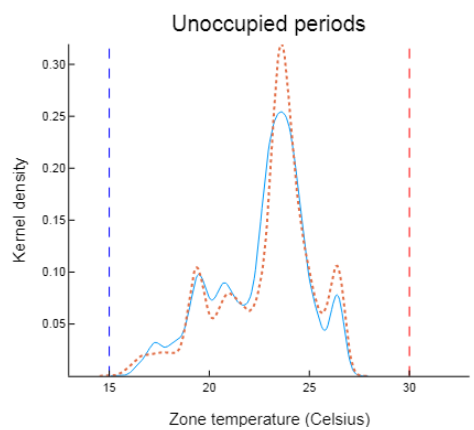


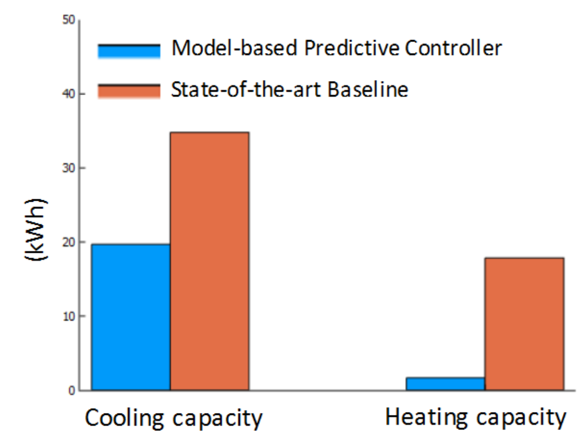
Baseline 1











Stakeholder Engagement

Technical Advisory Group meetings

- May 2017 – Project objectives, concept description, market evaluation
- Feb 2018 – Simulation model, baseline control implementation

Collaboration and coordination with other national laboratories

Marina Sofos
(Emerging Technologies)
Amy Jiron
(Commercial Buildings Integration)

Technical Advisory Group

Technical Advisory Group representing controls providers, technical experts, market users

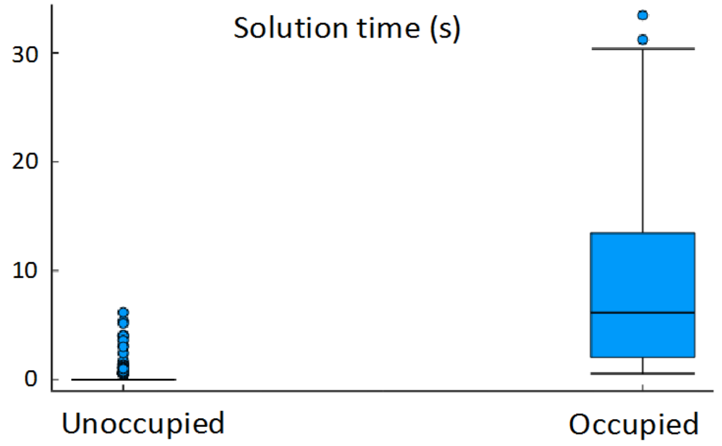
Vendors and service providers

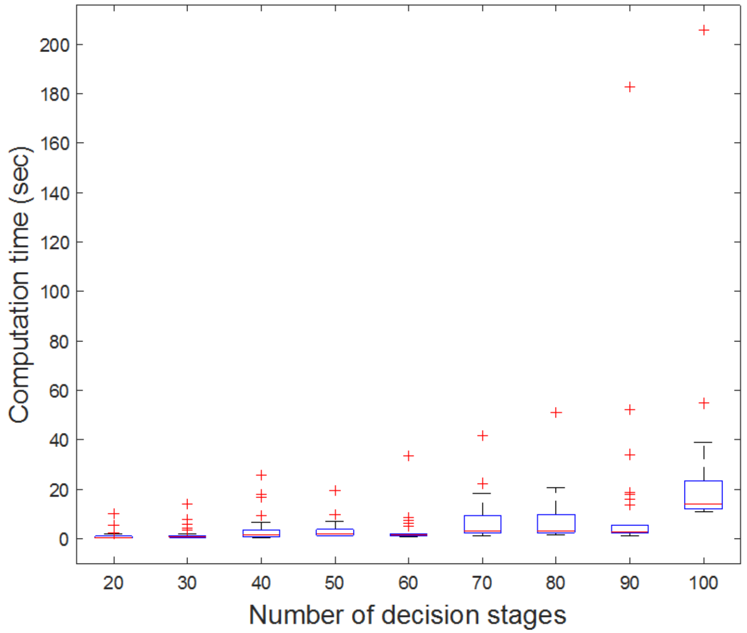
Technical SMEs

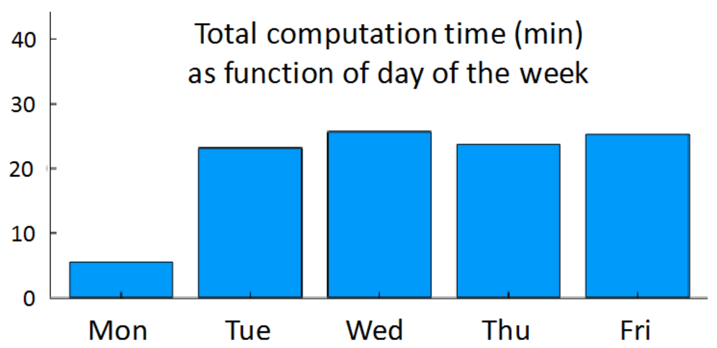
Market – owners and deployment

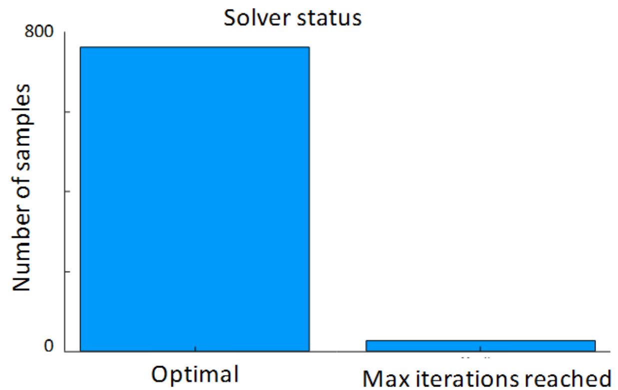
Remaining Project Work

Improvements on computational scalability



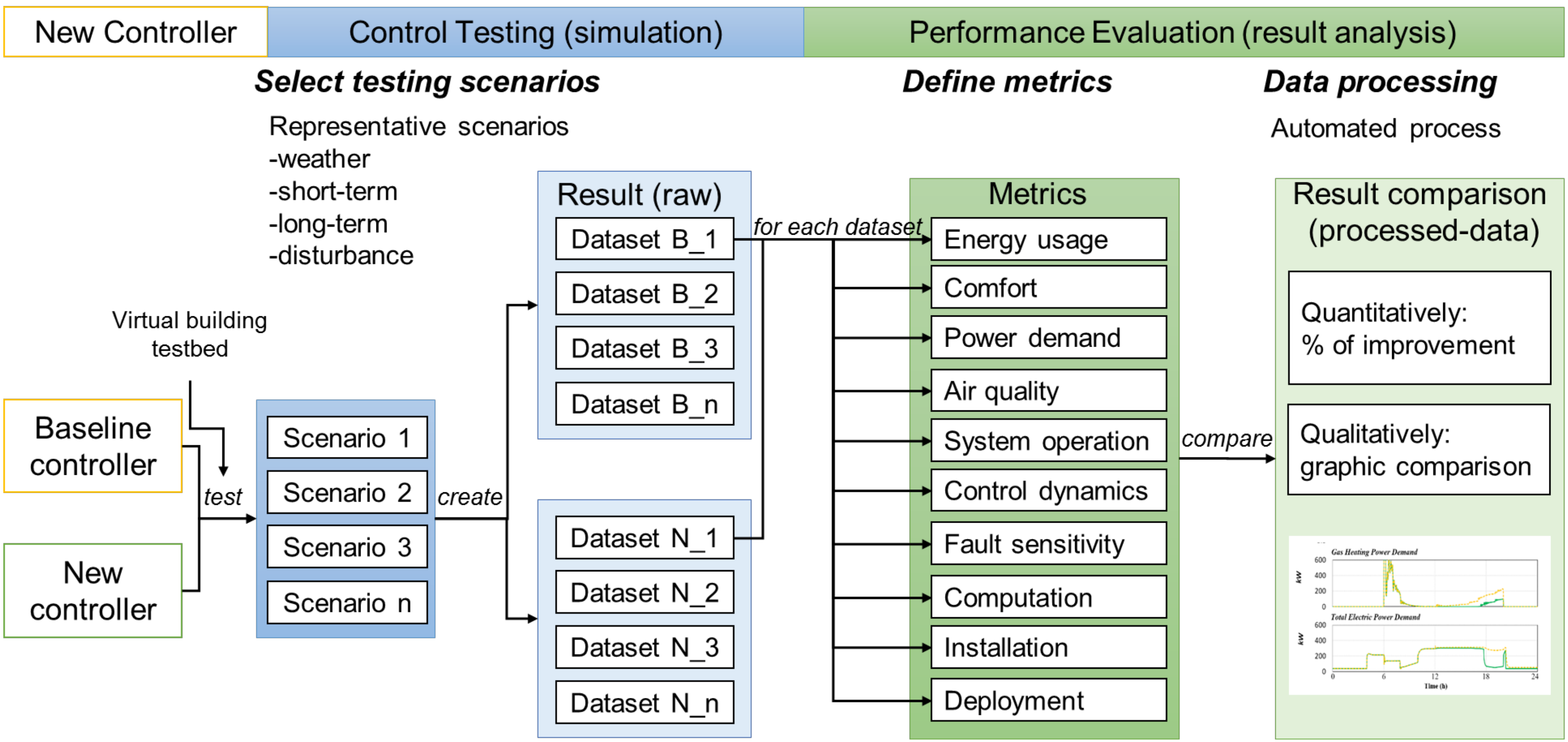






Remaining Project Work

Control Performance Evaluated in Simulation

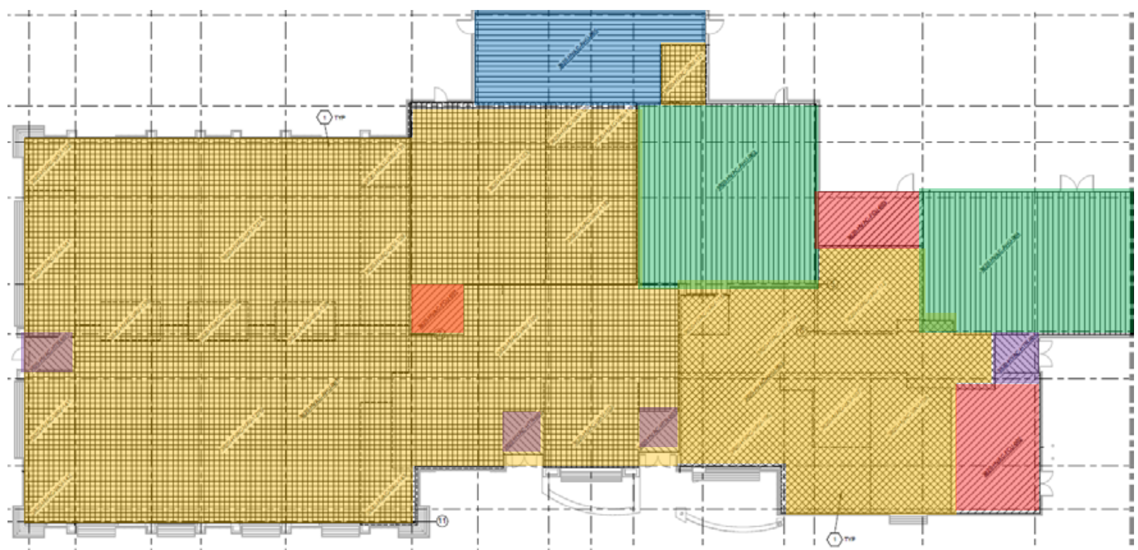


Remaining Project Work

Testing at PNNL's Systems Engineering Building Testbed

PNNL Richland Campus

System Engineering Building (SEB, 3820)
2,121m^2, Office + Laboratory
Operating Since 2015



- Roof Top Unit System
- Multiple-Zone VAV System
- Single-Zone VAV System
- Fan Coil System
- Data Center System

Thank You

Pacific Northwest National Laboratory
Draguna Vrabie
Draguna.Vrabie@pnnl.gov

Oak Ridge National Laboratory
Teja Kuruganti
kurugantipv@ornl.gov

REFERENCE SLIDES

Project Budget

Project Budget: 2100K (700K/year)
Variances: None
Cost to Date: 1000K

Budget History					
FY 2017 (past)		FY 2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
700K	0	700K	0	700K	0

Project Plan and Schedule

Project Schedule													
	Completed Work												
Project Start: 10/2016	Active Task (in progress work)												
Projected End: 09/2019	Planned Task (not started)												
	Go/No Go decision point												
	FY2017				FY2018				FY2019				FY2020
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Past Work													
Model-based testing infrastructure; barriers for technology to market transition													
Established Technical Advisory Group													
Defined experiment test procedures, Identified building test bed													
Machine learning methods with simulated data attain <5% RMSE accuracy													
Adaptive supervisory control demonstrated >15% energy consumption reduction													
Exploration for improving machine learning models. Adaptive optimal start.													
Current/Future Work													
Energy performance assessment with diverse operating conditions													
Online model learning with building data attain <5% RMSE accuracy													
Automated explanations of adaptive control decisions to building operators.													
VOLTTRON application for model characterization tested at building site													
Test procedure for evaluation of advanced control at building test site													
Multi-seasonal testing demonstrates model adaptation capabilities													
Adaptive control implementation tested at a building testbed site													

Stakeholder Engagement

Publications and presentations

- **2018 ASHRAE Building Performance Analysis Conference and SimBuild**
  - Sen Huang, Yan Chen, Paul Ehrlich, Draguna Vrabie, A control-oriented building envelope and HVAC system simulation model for a typical large office building
  - Yan Chen, Sen Huang, Draguna Vrabie, A Simulation Based Approach to Impact Assessment of Physical Faults: Large Commercial Building HVAC Case Study
- **2018 IEEE Conference on Control Technology and Applications (CCTA) Copenhagen, Denmark, August 21-24**
  - Optimal Energy Consumption Forecast for Grid Responsive Buildings: A Sensitivity Analysis, by Soumya Kundu, Thiagarajan Ramachandran, Yan Chen, Draguna Vrabie
- **2018 10th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes (SafeProcess 2018), Warsaw, Poland, August 29-31**
  - Indrasis Chakraborty, Draguna Vrabie, Fault Detection for Dynamical Systems using Differential Geometric and Concurrent Learning Approach
- **2019 ASHRAE Winter Conference, Atlanta, GA, January 12-16**
  - Jin Dong, Piljae Im, Sen Huang, Yan Chen, Jeffrey Munk, Teja Kuruganti, Draguna Vrabie, Development and Calibration of an Online Energy Model for an AHU Fan