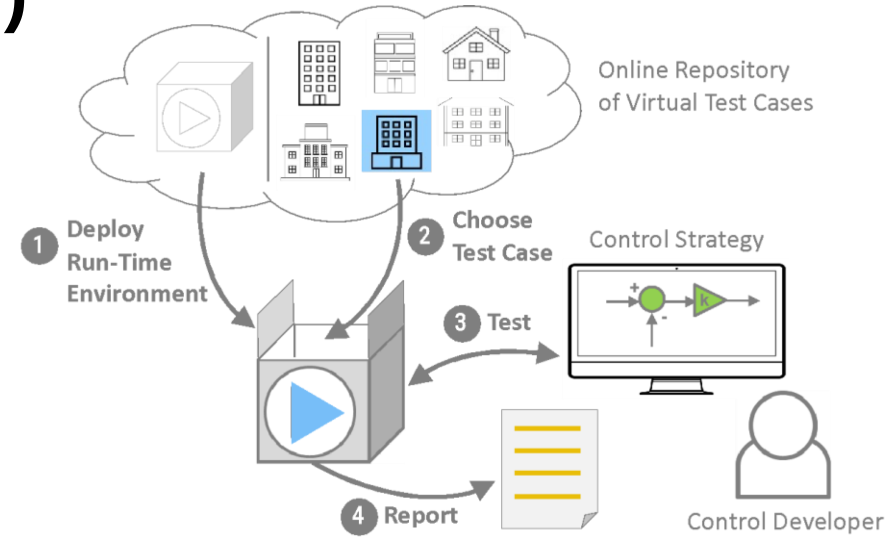
Building Optimization Testing Framework (BOPTEST)



LBNL, NREL, ORNL, PNNL, Arup, Johnson Controls

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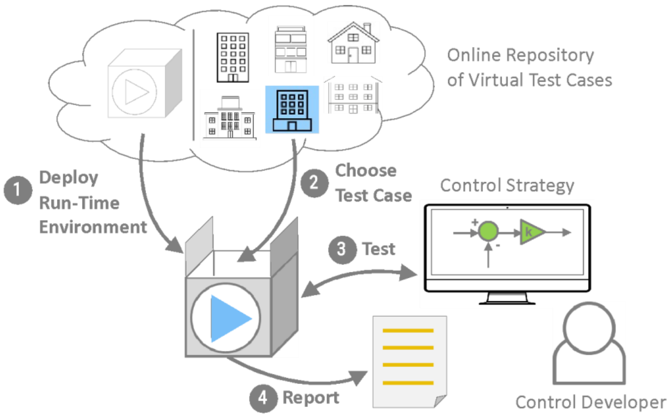
WBS 3.2.6.25

Project Summary

Objective and outcome

Enable virtual benchmarking and rapid prototyping of building HVAC control algorithms, including advanced algorithms such as MPC and Reinforcement Learning, which are critical for grid-interactive efficient buildings.



Team and Partners

LBNL: Project lead and software development
NREL: Web-service development
PNNL: Large office test case development and usage demonstration
ORNL: FRP test case development and calibration
Arup (cost share): Commercialization for controller evaluation services
Johnson Controls (cost share): BACnet interface and semantic models, user testing
IBPSA Project (not budgeted): International research and industry development partners

Stats

Performance Period:
Current FY23-FY25, Previously FY18-FY22

DOE budget:

Current FY23-FY25: DOE $550k/yr, Cost Share $300k/yr in-kind

Previously Spent FY18-FY22: $3.4 M

Milestone 1: BOPTEST available as a web-service Q1FY23

Milestone 2: BOPTEST 0.4.0 and Service 0.2.0 release Q2FY23

Problem

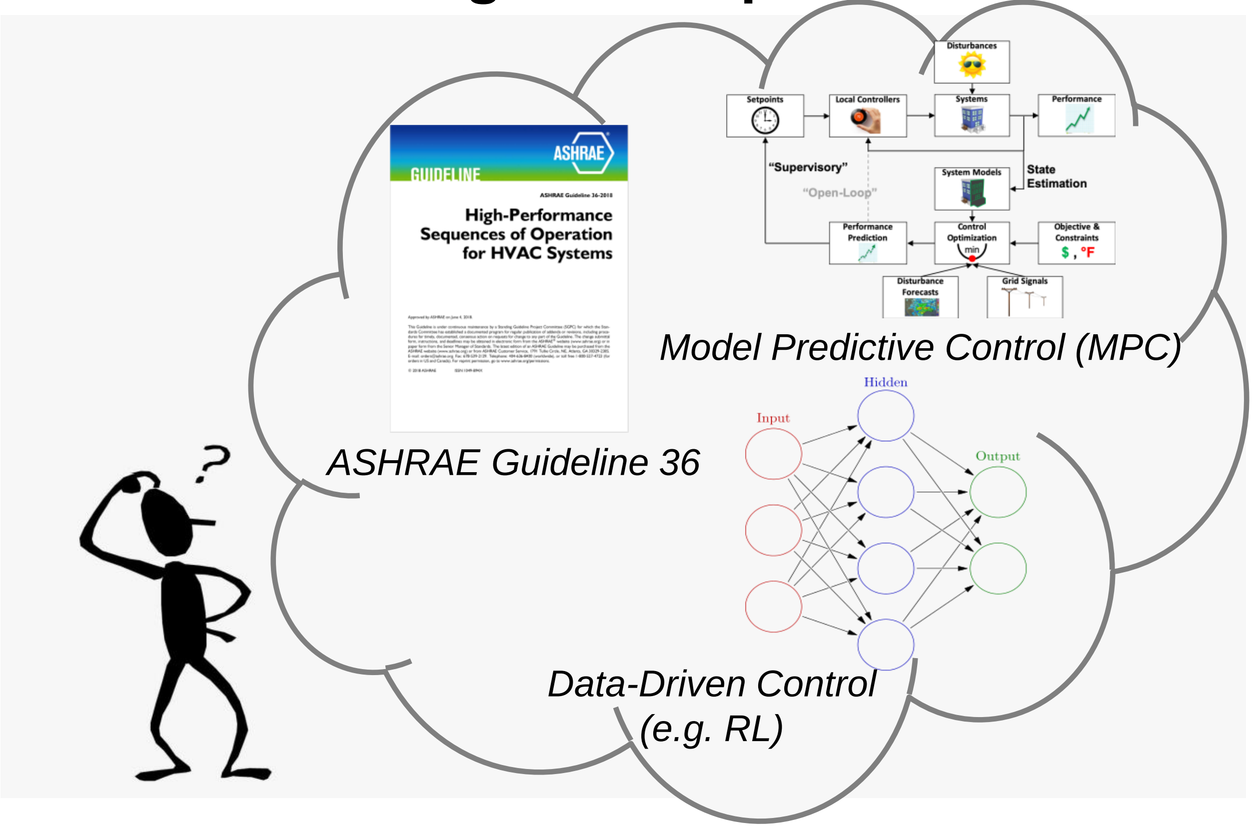
Many new and advanced control strategies hold promise …

But they all have different requirements for:

- Data
- Modeling
- Computation
- Expertise

How do they <u>compare</u> in terms of:

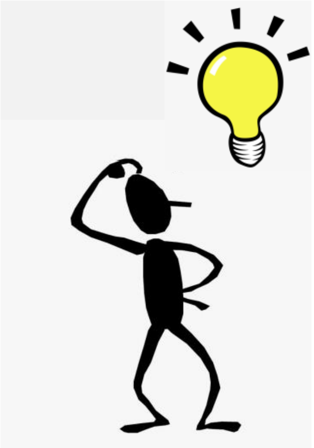
- Providing comfort
- Energy management
- Implementation cost
- Reliability



Alignment and Impact

Comparative evaluation would accelerate the development and deployment of new controls

Impact on stakeholders:



- **<u>Building and home owners</u>**
  Identify value among new and existing control products.
- **<u>Mechanical and control engineers</u>**
  Specify best strategies for climate, system, performance objectives.
- **<u>Control developers</u>**
  Streamline development and deployment of new control products.
- **<u>Policy makers and code bodies</u>**
  Establish performance expectations and design incentive programs.
- **<u>Educators and workforce development programs</u>**
  Train students on control performance expectations and commissioning

Approach: How is it done today?

Individualized case studies

- Findings are specific to building, HVAC, climate, study period, performance metrics, baseline controls
- Difficult to replicate and extend to new control strategies in future studies
- Effort and expertise to set up case study (real and simulated buildings) limits rapid prototyping and development by experts in fields outside building industry

Real or simulated buildings for control evaluation

Characteristic	Real	Simulated
Can be faster than real time	Disadvantage	Advantage
Low operational risk	Disadvantage	Advantage
Replicability and experimental control	Disadvantage	Advantage
Flexible set up (system, climate, data, control)	Disadvantage	Advantage
Realistic	Advantage	Disadvantage

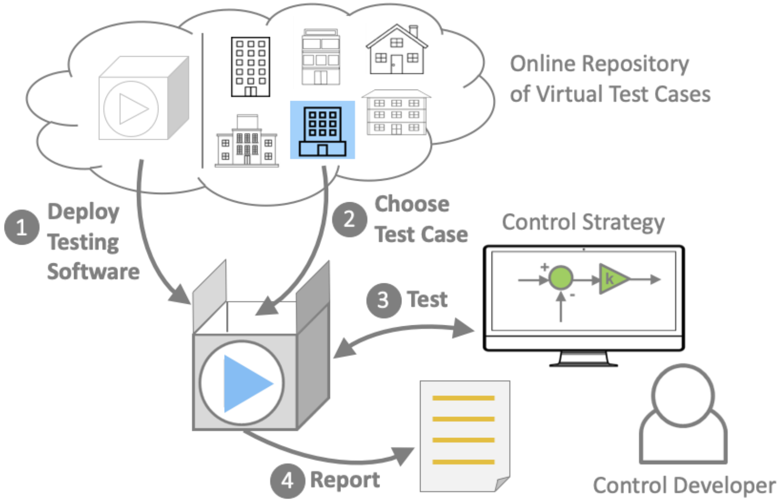
Can be addressed with state-of-the-art modeling tools

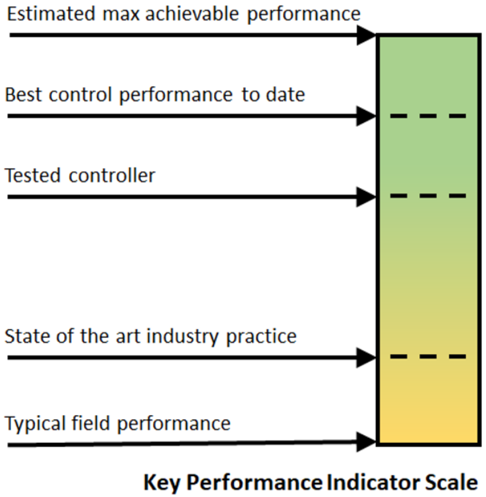
Approach: Concept

Building Optimization Testing Framework (BOPTEST)

A Simulation-Based Controls Testing and Benchmarking Environment

- Deployable software runtime environment: rapidly, repeatably, and at scale
- Control-interactive high-fidelity emulator models with defined boundary conditions
- Standardized key performance indicators (KPI) that are auto-calculated

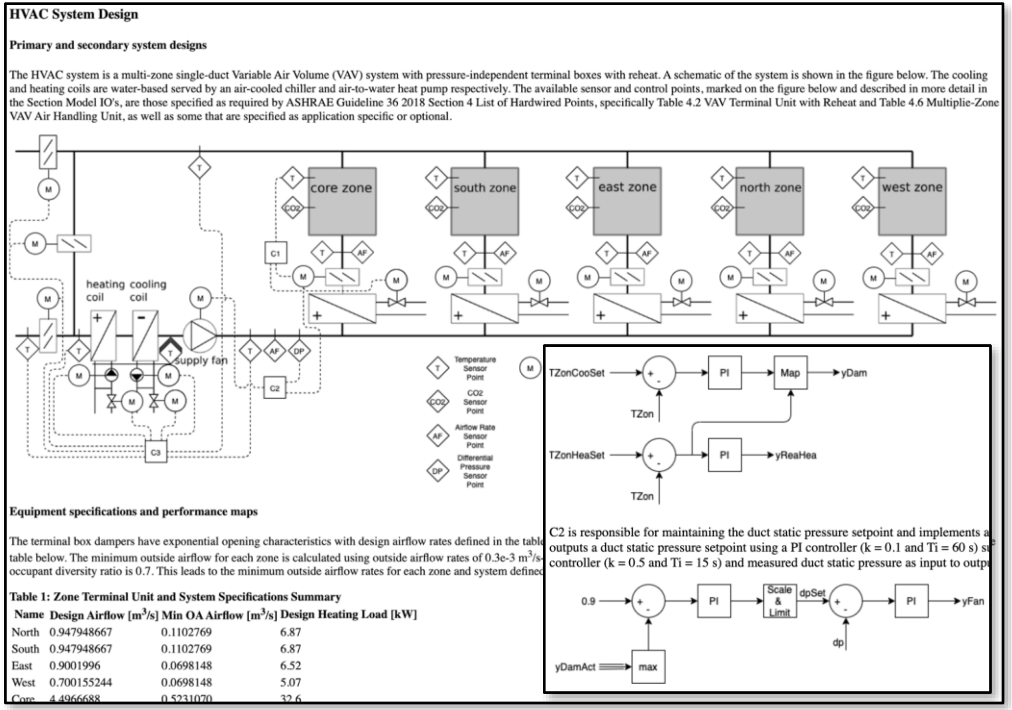




Approach: Technical

Building Emulators (“Test Cases”)

- High-fidelity models with embedded baseline control in Modelica, Spawn, and CDL
- Overwritable supervisory or local-loop control
- All boundary condition data defined (e.g. weather, schedules, electricity prices, carbon emission factors)
- Controlled exposure of sensor and control points
- Documentation and peer review to ensure quality and usability



HVAC System Design

Primary and secondary system designs

The HVAC system is a multi-zone single-duct Variable Air Volume (VAV) system with pressure-independent terminal boxes with reheat. A schematic of the system is shown in the figure below. The cooling and heating coils are water-based served by an air-cooled chiller and air-to-water heat pump respectively. The available sensor and control points, marked on the figure below and described in more detail in the Section Model IO's, are those specified as required by ASHRAE Guideline 36 2018 Section 4 List of Hardwired Points, specifically Table 4.2 VAV Terminal Unit with Reheat and Table 4.6 Multiplie-Zone VAV Air Handling Unit, as well as some that are specified as application specific or optional.

Equipment specifications and performance maps

The terminal box dampers have exponential opening characteristics with design airflow rates defined in the table
table below. The minimum outside airflow for each zone is calculated using outside airflow rates of 0.3e-3 m³/s
occupant diversity ratio is 0.7. This leads to the minimum outside airflow rates for each zone and system defined

C2 is responsible for maintaining the duct static pressure setpoint and implements a
outputs a duct static pressure setpoint using a PI controller (k = 0.1 and Ti = 60 s) s
controller (k = 0.5 and Ti = 15 s) and measured duct static pressure as input to outp

Table 1: Zone Terminal Unit and System Specifications Summary

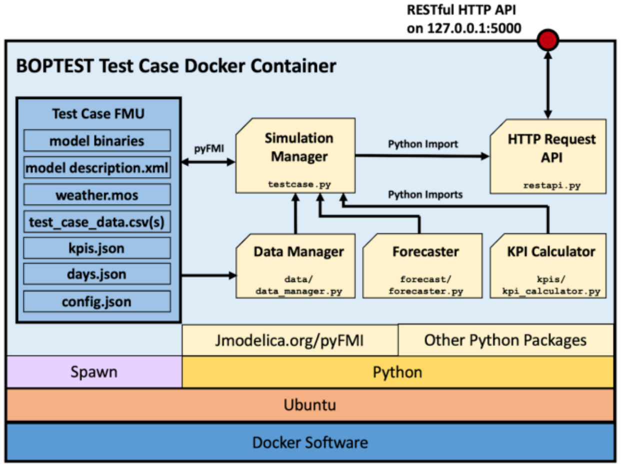
Name	Design Airflow [m^3/s]	Min OA Airflow [m^3/s]	Design Heating Load [kW]
North	0.947948667	0.1102769	6.87
South	0.947948667	0.1102769	6.87
East	0.9001996	0.0698148	6.52
West	0.700155244	0.0698148	5.07
Core	4.4966688	0.5231070	32.6

Example test case documentation snippets

Approach: Technical

Run-Time Environment

- Rapid, repeatable deployment locally cross-platform or as web-service using Docker
- Simulation management using Functional Mockup Interface (FMI)
- HTTP RESTful API for test management and controller interaction



Run-time environment architecture

Evaluation Design

- Set of KPIs calculated by framework
- Predefined test scenarios
(e.g. time period and electricity prices)
- Online dashboard for collecting, viewing, and comparing KPI results

Description	Unit
Energy Use	kWh / m^2
Energy Cost	$ / m^2
Emissions	KgCO2 / m^2
Thermal Discomfort	K.h / zone
IAQ Discomfort	ppm.h / zone
Peak Elec/Gas/District Demand	kW / m^2
Computational Time Ratio	[-]

KPIs calculated by BOPTEST

Approach: Community Engagement

IBPSA International Collaboration

- BOPTEST developed under IBPSA Project 1 WP1.2 (https://ibpsa.github.io/project1)
- Significant contributions to design, software, test cases, outreach, and user-testing
- Continuing IBPSA Project (2023-2027) proposed to IBPSA Board with 18 institutions

IBPSA Project 1

Biannual Technical Advisory Group (TAG) Meetings

- General feedback on approaches and outcomes, average 9 participants from FY19-FY22

EBC IEA Annex 81 on Data-Driven Smart Buildings

- Subtask B.3 utilizing BOPTEST for evaluation of data-driven control strategies (https://annex81.iea-ebc.org/)

EBC
Energy in Building and Communities Programme

Approach: Risks and Mitigation

Risk	Mitigation
Test cases are not realistic	• Modelica for realistic HVAC network pressure-flow physics and explicit control logic
Test case models are complex and difficult to scale to larger buildings	• Leverage Modelica library and tool development through Spawn, OBC, and IBPSA and international Modelica communities
Not generalizable to many control strategies	• Can override set points or actuator control, allowing for replacing part or all of the baseline control logic • Flexible control step time interval
No adoption by control developers and industry	• Engage with IBPSA Project, industry partners, TAG, IEA Annex 81, ASHRAE • Workshops, tutorial, and documentation • Interfaces: HTTP RESTful, BACnet, VOLTTRON, OpenAI-Gym

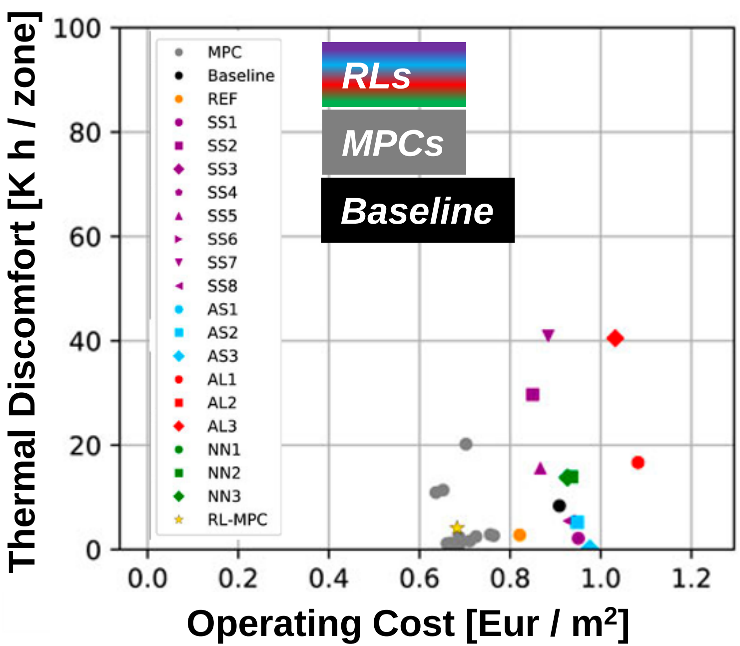
Progress: Framework Availability

- BOPTEST v0.4.0 for core framework software and test cases
- BOPTEST-Service v0.2.0 deployed as public web-service serving users at scale

Hydronic	Air
Single zone + Radiator	Single zone + FCU
Single zone + Floor heat and heat pump	Single zone + RTU with DX, gas furnace
2 zone + Floor heat and heat pump	2 zone + FCUs + AHUs with gas boiler, chiller
8-Zone + Radiators, boiler, and split cooling	5-Zone + 1 VAV AHU with reheat with chiller and heat pump
Single zone class + Radiator, AHU, CO2 control	10-zone + 1 VAV RTU with reheat, DX, electric heating
	15-Zone + 3 VAV AHU with reheat, chiller, boiler

Available *Implemented, but not yet available*

Test case development progress within IBPSA Project



Example MPC and RL benchmarking (Arroyo et al. 2022 https://doi.org/10.3389/fbuil.2022.849754)

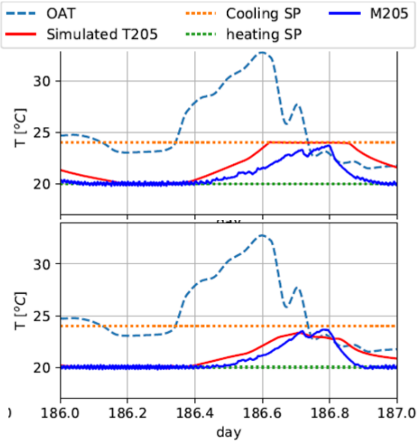
Progress: Test Case Development

Flexible Research Platform (FRP)

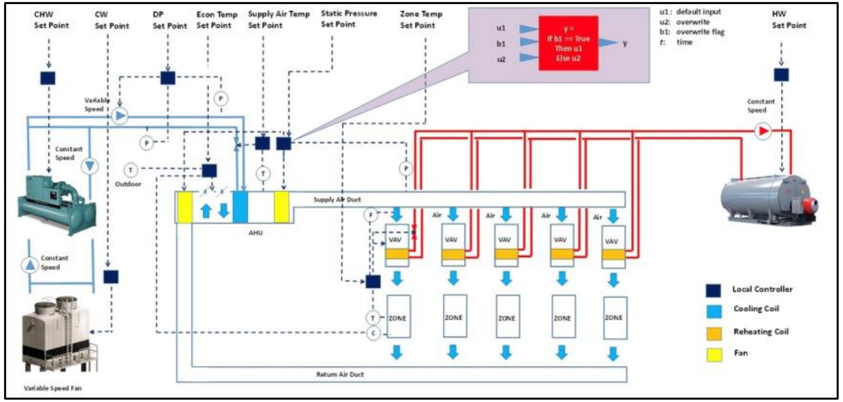
- 10-zone + 1 VAV RTU with reheat, DX, electric heating
- Calibrating with real-world behavior
- Simple step tests
- Normal operation tests

Large Office

- 15-Zone + 3 VAV AHU with reheat, chiller, boiler
- Has been used for MPC testing
- Refactored for usage with Spawn



ORNL FRP test facility (left) and initial calibration result snippets for 2 zones (right)



Large Office test case (left)

Progress: Use for Value Identification

ARUP (USA, Australia, UK)

- Adopting to provide building owners comparative performance evaluations for predictive, data-driven, and grid-interactive controls
- Last year focused on due diligence on BOPTEST and Modelica ecosystems
- Conducting building owner and control provider interviews

BOPTEST enables comparative control evaluation

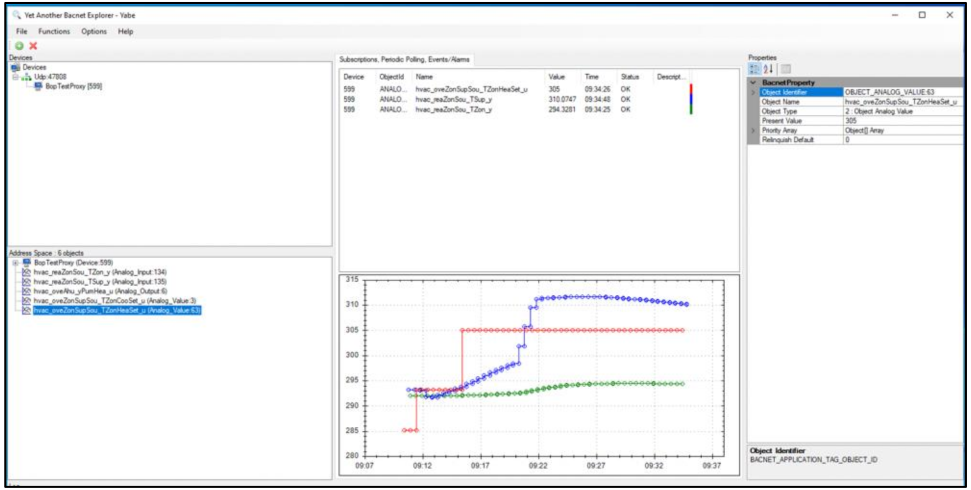
EPA EnergyStar (USA)

- Improve upon Smart Thermostat rating system
- See related project “Smart Thermostat Benchmarking”

Progress: Use by Control Providers

Johnson Controls (USA)

- Using to improve deployment process of new control products
- Prototyped BACnet interface and Semantic model usage for real-time use with control products
  (*Fierro et al. 2022 https://dl.acm.org/doi/pdf/10.1145/3563357.3564060*)



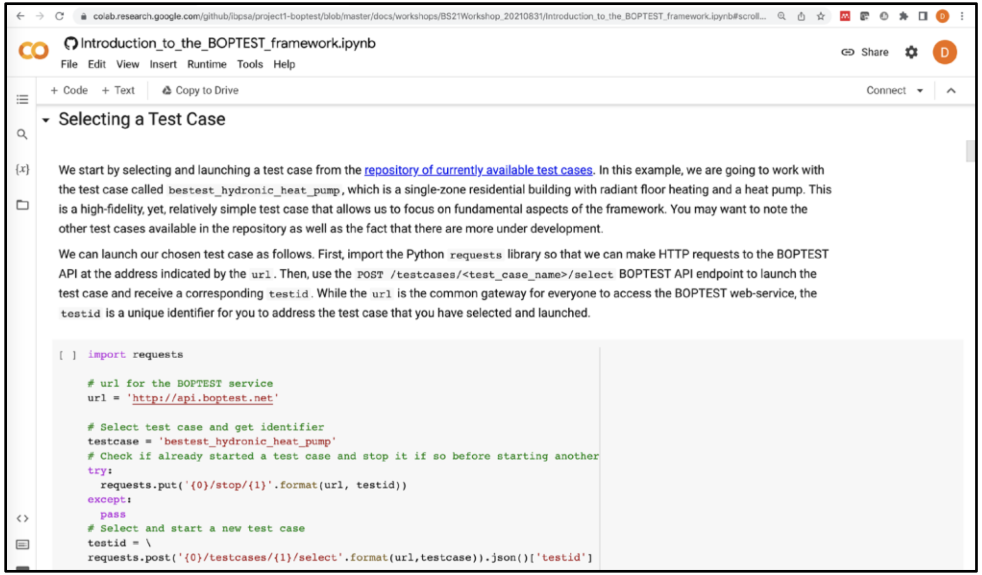
Example BACnet application communicating with BOPTEST (courtesy Erik Paulson, Johnson Controls)

Edo Energy (USA)

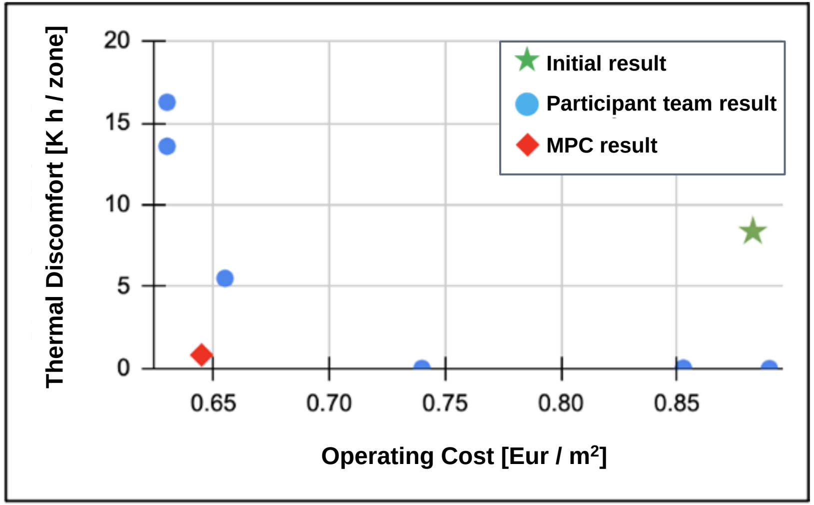
- Using to mature MPC control solution before deployment
- Participant in DOE-funded Connected Communities demonstrations

Progress: Use in Workshops

- Used BOPTEST-Service and Google Colab
- Three workshops: IBPSA BS21 (Aug 2021, 15 ppl), Energyville (Oct 2021, 17 ppl), Climate Change AI Summer School (Aug 2022, ~60 ppl)



Google Colab notebook used for workshops at IBPSA BS21 and Energyville
https://github.com/ibpsa/project1-boptest/blob/master/docs/workshops/BS21Workshop_20210831/Introduction_to_the_BOPTEST_framework.ipynb



IBPSA BS21 exercise results where teams were tasked to improve provided feedback controller and also compare with previously-implemented MPC controller

Lessons Learned and Future Work

Challenges and Lessons Learned

- Effort and expertise needed to design and implement high-quality, robust test cases
- Robustness of large and complex test case models
- Breadth of application areas and user requests for test cases, scenarios, and KPIs

Test Case Development

- Flexible Research Platform and Large Office test cases available (FY23)
- Expand test case offerings for new applications
  (through IBPSA Project and industry collaboration), such as:
  - New building types, such as K-12, hospitals, or data centers
  - Buildings with DER or TES
  - District heating, cooling, electrical networks

Future Work

Key Software Development

- Maintain software and respond to user feedback (6-month release cycle)
- Harden BACnet interface (Q3FY23) and semantic models (Q3FY24)
- Additional testing scenarios representing more realistic building operation (Q2FY24)
- Work with research and industry partners to trial new features and build out controller evaluation services (FY24-FY25)

Thank You

LBNL, NREL, ORNL, PNNL, Arup, Johnson Controls
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REFERENCE SLIDES

Project Execution

	FY23				FY24				FY25			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Planned DOE Budget ($)	555k				550k				550k			
Spent DOE Budget ($)	221k											
Past Work												
Scoping and prioritization for new BOPTEST Web Service APIs and features.	x											
BOPTEST Web-Service moved to a separate GitHub repository from BOPTEST Core	x		x									
A new BOPTEST Web Service version is deployed		x										
FRP Documentation of test case development		x										
OpenModelica integrated as test case compiler option in parser.		x										
Semi-annual TAG meetings with minutes and slides distributed to TAG members.		x										
Semi-annual BOPTEST version release on GitHub.		x										
Current/Future Work												
Scoping and prioritization for new scenarios representing realistic building operation.	x		x									
Develop a demonstration showcase to engage with potential users in relevant venues			x									
BACnet-BOPTEST available on GitHub and ready for version release.			GNG									
At least one test case generated by Arup ready for peer review.				x								
BOPTEST Dashboard updates.					x							
JCI control product tested with BACnet-BOPTEST interface with memo report.					x							
New scenarios for realistic building operation available on GitHub and ready for version release.						x						
Semantic modeling capability available on GitHub and ready for version release.							GNG					
Arup-engaged control vendor product tested with BOPTEST with memo report.								x				
At least one more test case generated by Arup ready for peer review.								x				
JCI control product tested with Semantic modeling capability with memo report.									x			
Engagement with industry clients identified by Arup.										x		
Web-Service production version deployed.											GNG	
Final BOPTEST version released on GitHub.												x
Semi-annual TAG meetings with minutes and slides distributed to TAG members.				x		x		x		x		x
Semi-annual BOPTEST version release on GitHub.				x		x		x		x		x
A new BOPTEST Web Service version is deployed.				x		x		x		x		x

Red x indicates originally planned

Web-Service established within own open-repository earlier in project.

Scoping and prioritization for new scenarios representing realistic building operation milestone delayed as Arup investigates BOPTEST and Modelica ecosystems and tools.

Team

LBNL	Project lead, software development, leads IBPSA collaboration and Annex 81 Subtask B3	• David Blum • Ettore Zanetti • Michael Wetter
NREL	BOPTEST-Service development and deployment	• Kyle Benne • Tim Coleman
PNNL	Large office test case development and usage demonstration	• Yan Chen • Xing Lu • Draguna Vrabie
ORNL	Flexible Research Platform (FRP) test case development and calibration	• Yeonjin Bae • Sen Huang • Piljae Im
Arup	Adoption for commercialized controller evaluation services for building owner clients, market research, test case and scenario development	• Haico Schepers • Raffe Brennan • Justin Prince • Robert Knight • Tom Beischer
Johnson Controls	BACnet interface development, semantic model integration, framework utilization for improving control deployment process	• Erik Paulson