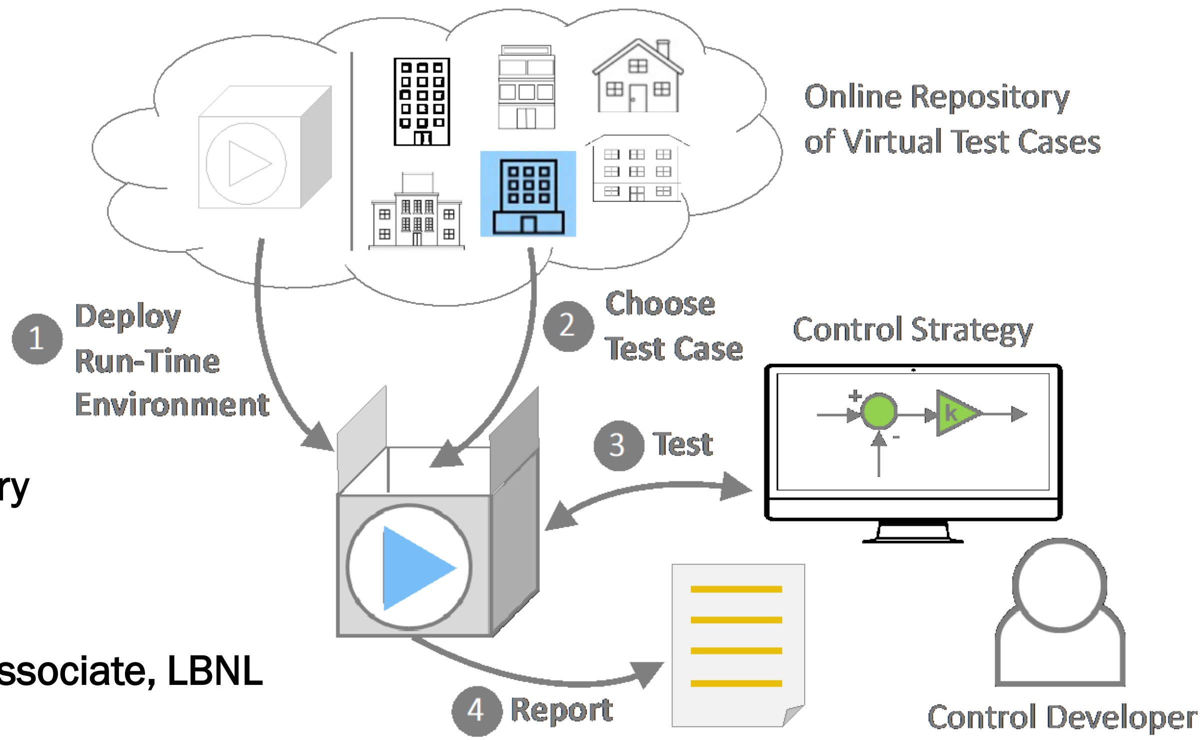
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Building Optimization Testing Framework (BOPTEST)



LBNL, PNNL, NREL, ORNL, Devetry

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Project Summary

Timeline:

Start date: 10/1/2019 (FY20)
(Preliminary project started 1/1/2018)
Planned end date: 9/30/2022 (FY22)

Key Milestones

1. Test case repository added to GitHub; 9/30/2020
2. Software version 0.1.0 release on GitHub; 6/30/2021

Budget:

Total Project $ to Date:

- DOE: $1.65 mil FY20-FY21
  (Preliminary funding for FY18 & FY19 was $1.25 mil)
- Cost Share: No direct, but leverage contributions from partner institutions through IBPSA Project 1 for FY18-FY22.

Total Project $:

- DOE: $2.4 mil FY20-FY22
  (Including FY18 & FY19 $3.65 mil)
- Cost Share: No direct, but leverage contributions from partner institutions through IBPSA Project 1 for FY18-FY22.

Key Partners:

Institutions from IBPSA Project 1 that jointly develop Modelica & FMI for buildings, particularly:	
Katholieke Universiteit (KU) Leuven	IK4 Tekniker
Southern Denmark University	SINTEF
Polytechnic University of Milan	ENGIE Lab
ETH Zurich / EMPA	DeltaQ
University of Colorado Boulder	

Project Outcome:

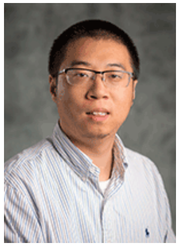
Enable benchmarking and rapid prototyping of building HVAC control algorithms, including advanced algorithms such as MPC and Reinforcement Learning, which are critical for grid-interactive efficient buildings. Done by:

1. Developing a rapidly, repeatably, deployable run-time environment (RTE) for building emulation with HTTP API.
2. Developing a set of common building emulators that utilize Modelica and FMI and make possible control signal overwriting by test controllers at the supervisory and local-loop level.
3. Specifying common Key Performance Indicators (KPI) calculated within the RTE using data from building emulators.

Team


David Blum


Michael Wetter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Philip Gonzalez


Yeonjin Bae


Piljae Im

LBNL

- Core software design and development
- Test case design and development
- Lead coordination with IBPSA Project 1 and IEA Annex 81

PNNL

- Core software design and development
- 15-zone office test case development
- Example feedback and MPC controller development and testing

NREL and Devetry (sub to NREL)

- Web-service design and development
- Results dashboard design and development (with Devetry)

ORNL

- FRP test case development and calibration

Challenge

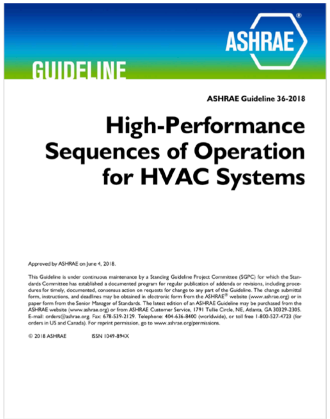
Needs for Improved Controls

- Energy efficiency, grid-interactivity, resiliency
- New system architectures and onsite generation and storage

Challenge 1: Individualized Studies

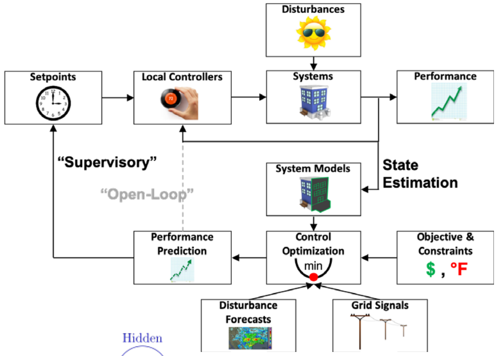
- Different building, HVAC, climate, study period, performance metrics
- Demonstrated savings/advantages depend on comparative baseline [1]

→ **Difficult to answer which approach is most effective and where more work needed**

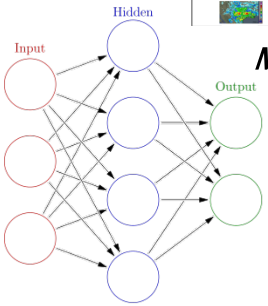


ASHRAE
GUIDELINE
ASHRAE Guideline 36-2018
High-Performance Sequences of Operation for HVAC Systems

ASHRAE Guideline 36



Model Predictive Control (MPC)



Data-Driven Control

Examples of recent controls development

Challenge 2: Building Emulator Time and Effort

- Real buildings pose operational risks and have slow-changing operating conditions
- Realistic simulations require building modeling expertise and effort

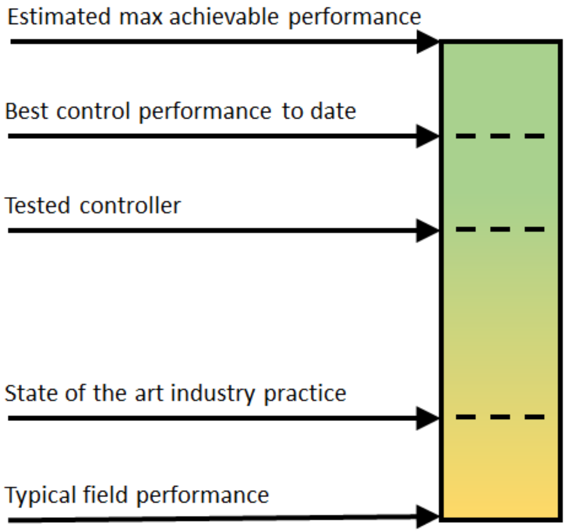
→ **Limits rapid prototyping and algorithm development opportunities from outside experts (e.g. process control, optimization, data science)**

[1] For example for VAV Systems, range of 12-67% savings of "good practice" controls depending on if compared to "average" or "poor" practices [1]

Approach

Goals:

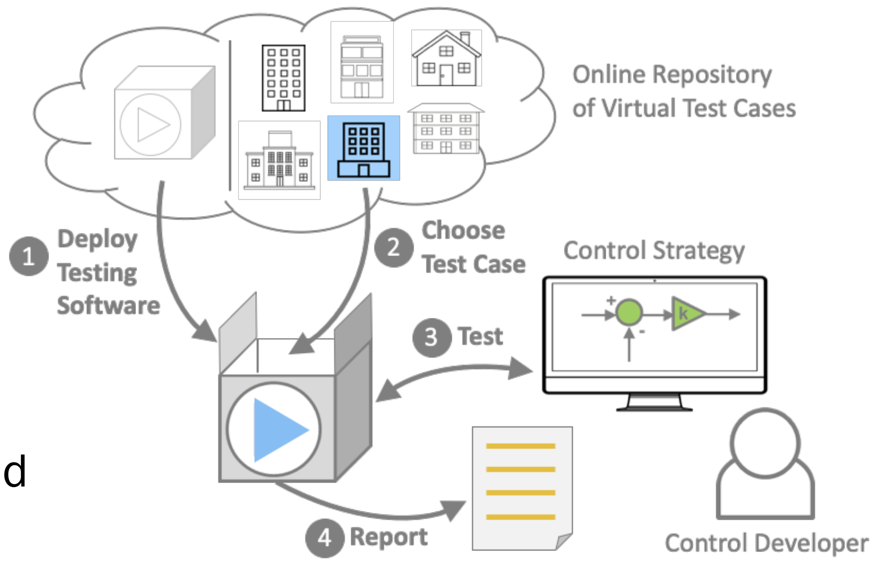
- Establish and benchmark state-of-the-art performance of control for building energy systems
- Accelerate building control software development and provide control developers with performance information
- Enable transition and encourage adoption of advanced building control algorithms



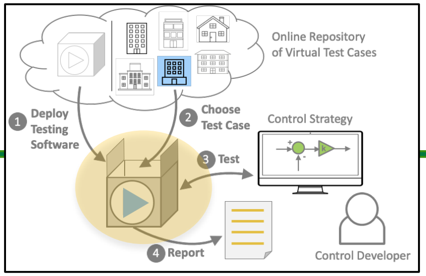
Key Performance Indicator Scale

Achieved by:

- Developing a *software framework* for testing and evaluation of advanced building control
- Developing *common sets* of building emulators, test scenarios, and key performance indicators (KPI)
- User engagement to capture expected use cases and facilitate the utilization in the broad academic and industry R&D communities

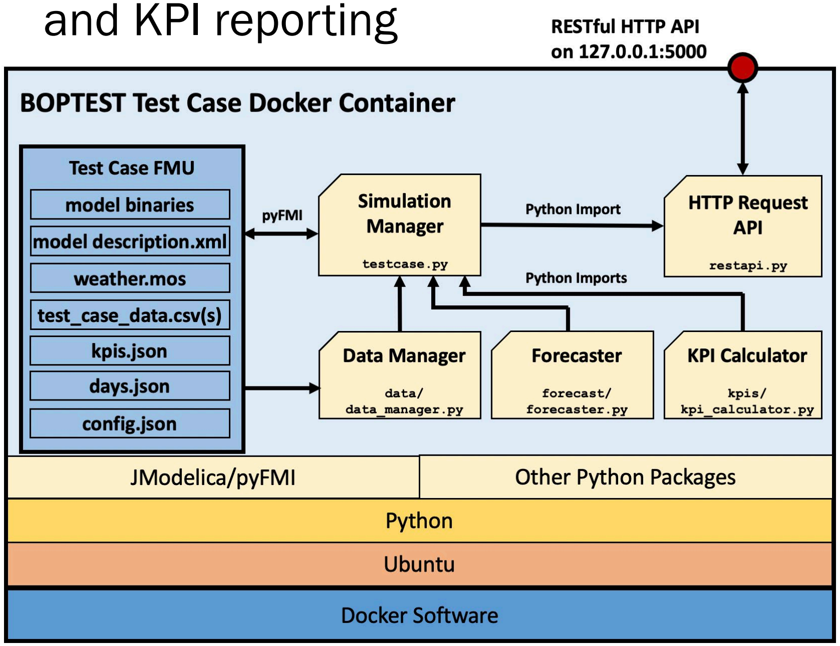


Approach



Software Framework

- Simulation management based on Functional Mockup Interface (FMI)
- Rapid, repeatable deployment locally or as web-service using Docker
- HTTP-based RESTful API for test set up, emulator-controller co-simulation, and KPI reporting

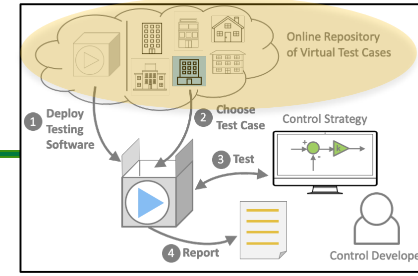


RTE Architecture

API Endpoint	Description
GET *measurements*	Receive available measurement points
GET *inputs*	Receive available input points
PUT *scenario*	Set test scenario
PUT *initialize*	Initialize simulation
PUT *step*	Set control step
GET *forecast*	Receive forecasts
POST *advance*	Advance simulation with control input
PUT *results*	Receive historic point trajectory
GET *kpi*	Receive KPI values

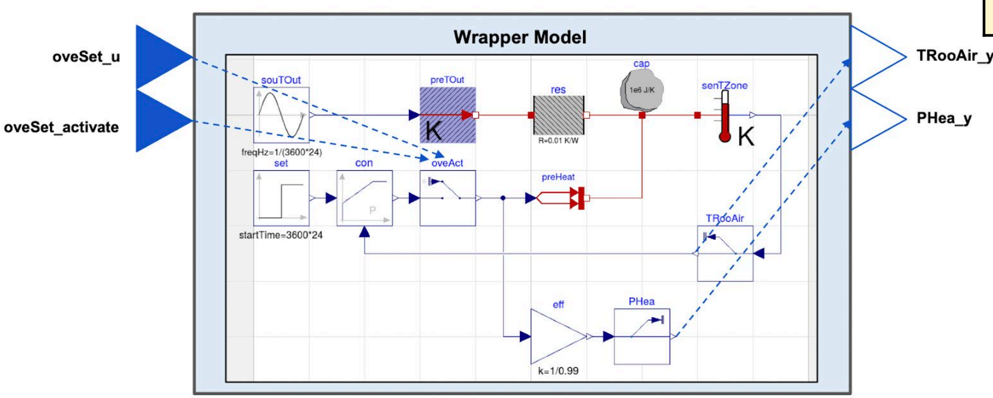
Key RESTful HTTP API Endpoints

Approach



Common Set of Building Emulators

- High-fidelity models with embedded baseline controllers in Modelica exported as FMUs
- All boundary condition data included (e.g. weather, schedules, electricity prices)
- Range of building types, sizes, and systems
- Overwrite supervisory or local-loop control
- Practical control and measurement points
- Documentation



Example Modelica model with read/write points

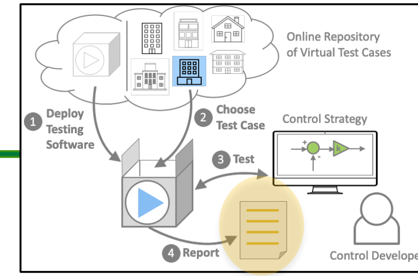
Hydronic	**Air**
Single zone + Radiator	Single zone + FCU
Single zone + TABS	5-Zone + 1 VAV AHU (distr. only)
8-Zone + Radiators and split cooling	10-zone + 1 VAV with DX, electric heating (FRP)
Single zone class + Radiator, AHU	15-Zone + 3 VAV AHU, chiller, boiler

☐ Completed and available in repo

☐ Implemented in Modelica but not finalized in repo

Subset of planned building emulators defined under IBPSA Project 1

Approach

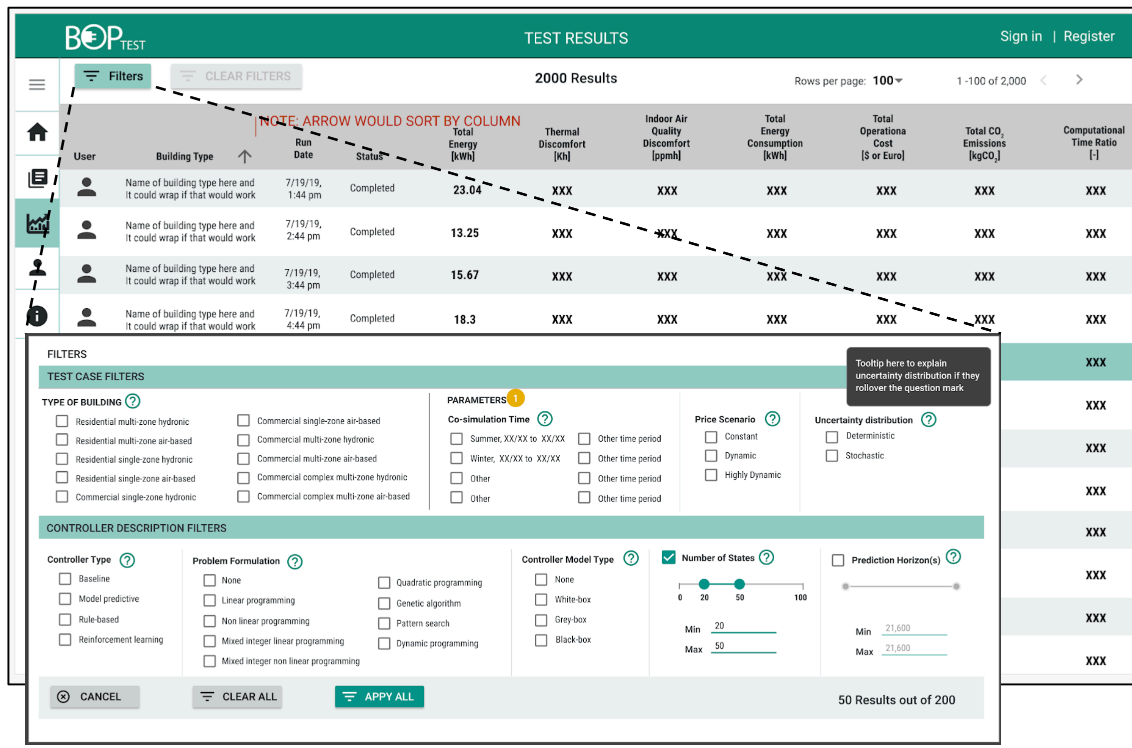


Common Evaluation Design

- Set of KPIs calculated by software framework for every test case
- Definition of testing scenarios for each emulator (e.g. time period and electricity prices)
- Capability for custom KPI calculation through access to test data
- Development of results sharing platform with initial implementation completed

1. Energy Use [kWh/m^2]
2. Energy Cost [\$/m^2]
3. Emissions [kg CO_2/m^2]
4. Thermal Discomfort [K h/zone]
5. IAQ Discomfort [ppm h /zone]
6. Computational Time Ratio [-]

Set of six KPIs evaluated for every test by software framework.



Mockups of online results sharing dashboard

Impact

Accelerate Controls Development

- Improved rule-based controls for commercial buildings can save 2.7 quads/yr (3% 2015 U.S. primary energy) and reduce peak electricity demand by 16% [2]
- Optimization-based controls such as MPC and RL
  - HVAC and lighting energy savings typically range 15-30% [3-7]
  - Peak demand reduction, load shifting, and other grid services [8-9]

Enable Controls Benchmarking

- Common test cases and KPIs allow for comparison of different algorithms from different developers, informing investment by building owners and future R&D focus
- Reported results establish collective baseline for future comparison

Open Opportunities

- Reduce the barriers (risk, effort, cost, modeling expertise) for control algorithm evaluation on realistic test cases
- Encourage control development by experts outside buildings community, such as process controls, optimization, and data science

Impact

Advancing the State of the Art for Evaluation Frameworks

- Integration of high-fidelity building simulation with containerized software deployment capable of being deployed locally or on cloud serving multiple, remote clients
- Use of Modelica and FMI standards for emulator models allow for:
  - Leveraging ~10 years of international, open-source model development under IEA EBC Annex 60 and IBPSA Project 1 as well as tool development in other industries
  - Flexible control points from supervisory set points to local actuator signals
- Provision of forecasts (e.g. weather, electricity prices) enables testing with predictive control algorithms and eventual evaluation under specified uncertainty scenarios

Supporting and Leveraging Other DOE Efforts

- Utilize Modelica and FMI technologies developed under Spawn and Buildings Library
- Baseline controllers embedded in emulators and test controllers may be implemented using CDL from OpenBuildingControl
- Alfalfa architecture used to implement BOPTEST as a web-service
- Development underway of VOLTTRON agent
- Useful for controls development and evaluation under Sensors and Controls portfolio

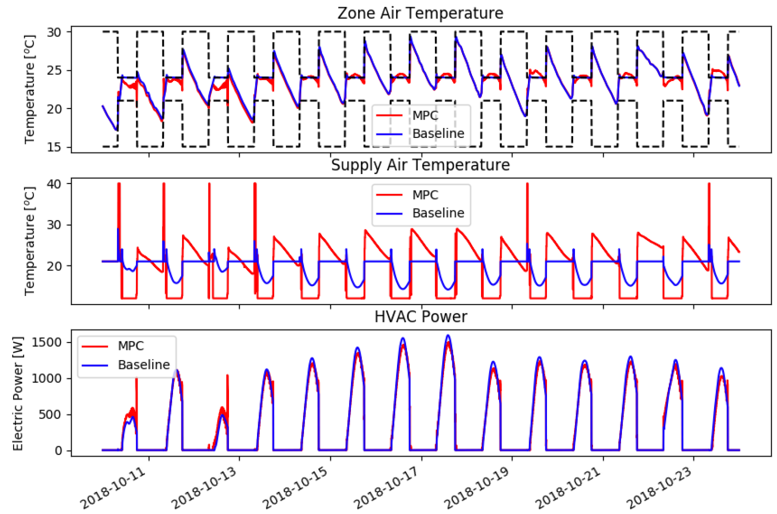
Progress

BOPTEST v0.1.0 (https://github.com/ibpsa/project1-boptest)

- Fully functional software framework deployable locally or on cloud as service serving multiple test controller clients (called “boptest-service”)
- Four building emulators available (+ three used for development purposes)
- Example test controllers in Python, Julia, and Javascript as well as MPC controller testing from 6 different institutions (IBPSA Project 1) validate the technical approach

```python
# TEST CONTROLLER IMPORT
# ------------------------------------------------------------------------------
from examples.python.controllers import pid
# ------------------------------------------------------------------------------
# SET TEST PARAMETERS
# ------------------------------------------------------------------------------
# Set URL for test case
url = 'http://127.0.0.1:5000'
# Set testing scenario
scenario = {'time_period':'test_day', 'electricity_price':'dynamic'}
# Set control step
step = 300
# ------------------------------------------------------------------------------
# GET TEST INFORMATION
# ------------------------------------------------------------------------------
# Get test case name
name = requests.get('{0}/name'.format(url)).json()
# Get inputs available
inputs = requests.get('{0}/inputs'.format(url)).json()
# Get measurements available
measurements = requests.get('{0}/measurements'.format(url)).json()
# ------------------------------------------------------------------------------
# RUN TEST CASE
# ------------------------------------------------------------------------------
# Set control step
requests.put('{0}/step'.format(url), data={'step':step})
# Set test case scenario
y = requests.put('{0}/scenario'.format(url), data=scenario).json()['time_period']
# Record test start time
start_time = y['time']
# Simulation Loop
while y:
    # Compute control signal
    u = pid.compute_control(y)
    # Advance simulation with control signal
    y = requests.post('{0}/advance'.format(url), data=u).json()
# ------------------------------------------------------------------------------
# GET RESULTS
# ------------------------------------------------------------------------------
# Get KPIs
kpi = requests.get('{0}/kpi'.format(url)).json()
# Get zone temperature over test period
args = {'point_name':'TRooAir_y', 'start_time':start_time, 'final_time':np.inf}
res = requests.put('{0}/results'.format(url), data=args).json()
```

Example controller interface code in Python



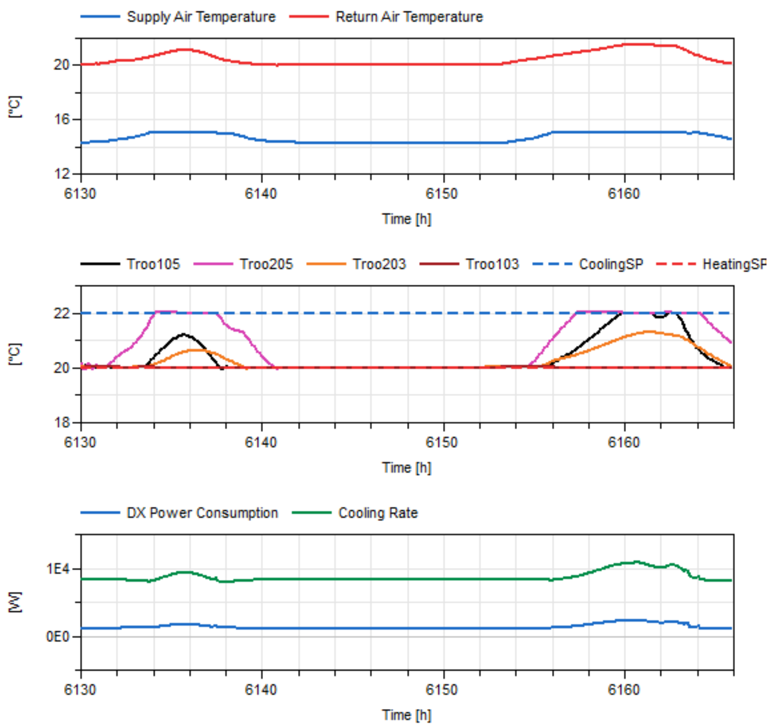
Controller	Energy [kWh/m²]	Cost [$/m²]	Emission [kg CO_2/m²]	Thermal Dis. [K h/zone]	IAQ Dis. [ppm h/zone]	Com. Ratio [-]
Baseline	2.226	0.1208	1.466	7.670	1222	1.192E-4
MPC	2.204	0.1186	1.442	23.69	1220	6.484E-3

Results of test using MPC with “BESTEST Air” case

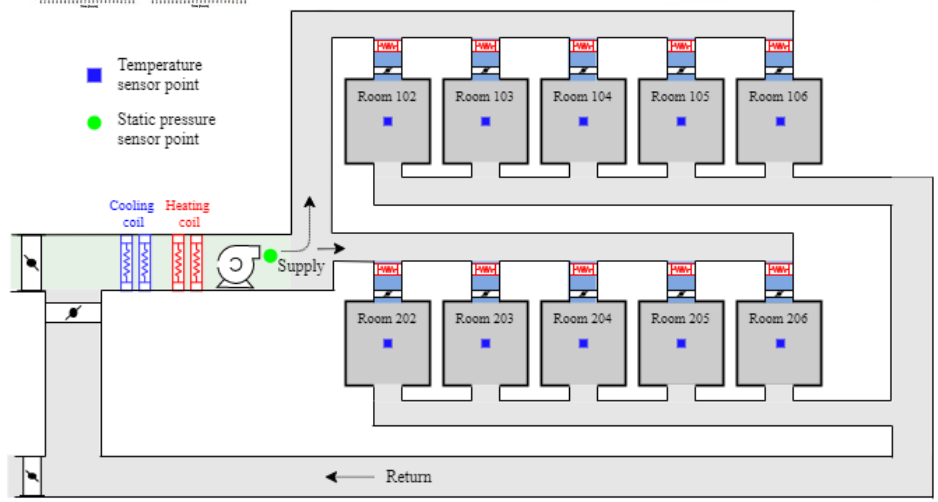
Progress

Test Case Development - FRP

- Initial model implemented in Modelica
- Begun data collection in real system for calibration and demonstration of realistic control emulation



Example results from Modelica model

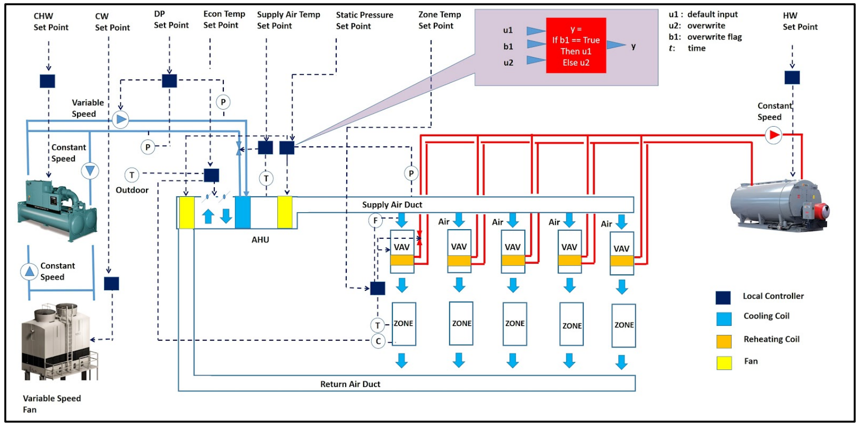


Schematic of ORNL FRP test building

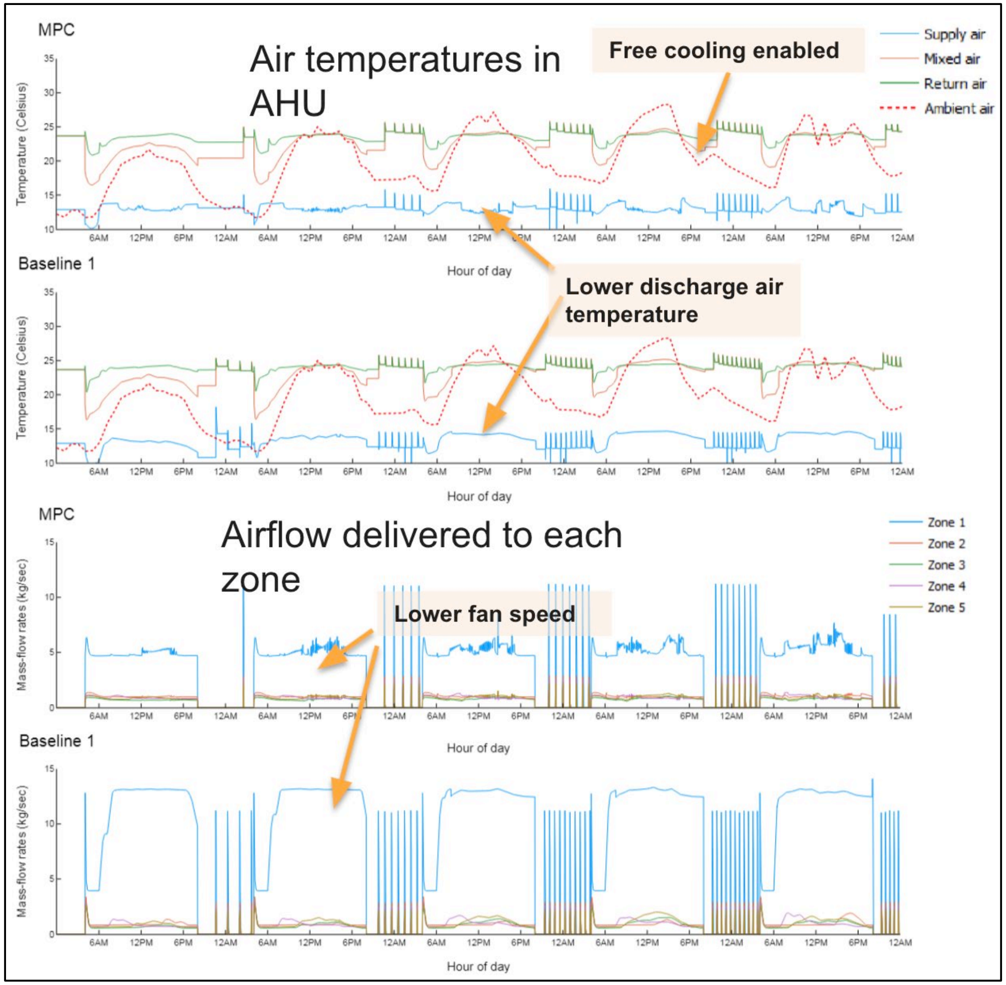
Progress

Test Case Development – 15-Zone Office

- 3 multizone VAV AHU w/ reheat, chilled water plant, and boiler plant
- Model implemented with Modelica-EnergyPlus co-simulation
- Utilized for comparison between baseline control and MPC control



System schematic showing AHU, chilled water, and hot water systems



Example results comparing MPC with baseline

Stakeholder Engagement

IBPSA Project 1

- https://ibpsa.github.io/project1
- BIM/GIS and Modelica Framework for building and community energy system design and operation
- Work Package 1.2 - MPC and BOPTEST
  - 25 participants from 13 institutions
  - Collaboration on emulator development, software development, and peer review
  - MPC testing and evaluation

Biannual Technical Advisory Group Meetings

- Representatives from academia and industry
- Feedback on project progress
- Average 11 participants

EBC IEA Annex 81 on Data-Driven Smart Buildings

- https://annex81.iea-ebc.org/
- Subtask B.3 – evaluation of data-driven control strategies to utilize BOPTEST

Remaining Project Work

Near Term (Through FY22)

- Key Emulator Development
  - Develop and make available single-zone commercial packaged RTU test case
  - Calibrate and make available FRP test case
  - Make available 15-zone office test case and utilize Spawn
- Key Software Development
  - Improved user guide and error handling/messaging
  - Prototype added meta-data tagging for control and measurement points
  - Add capability of filtering controller and test characteristics to results dashboard
- Usage and Stakeholder Engagement
  - Additional MPC and RL testing through IBPSA Project 1 and Annex 81
  - Workshop scheduled at IBPSA BS21 Conference, organize Hackathon later FY22

Long Term (FY23-25)

- Maintain and enhance software components to provide more test content
- Grow partnerships with industry to promote usage

References

[1] X. Pang, M. A. Piette, and N. Zhou (2017). “Characterizing variations in variable air volume system controls.” Energy and Buildings, vol. 135, pp. 166–175.

[2] Fernandez, J., Xie, Y., Katipamula, S., Zhao, M., Wang, W., and Corbin, C. (2017). “Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction.” Pacific Northwest National Laboratory Technical Report PNNL-25985.

[3] Siroky, J., Oldewurtel, F., Cigler, J., and Privara, S. (2011). “Experimental analysis of model predictive control for an energy efficient building heating system.” Applied Energy, 9, 3079-3087.

[4] Oldewurtel, F, Parisio, A, Jones, CN, Gyalistras, D, Gwerder, M, Stauch, V, Lehmann, B, and Morari, M. (2012). “Use of model predictive control and weather forecasts for energy efficient building climate control.” Energy and Buildings, 45:15-27.

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[6] West, S., Ward, J., and Wall, J. (2014). “Trial results from a model predictive control and optimisation system for commercial building HVAC.” Energy and Buildings, 72, 271-279.

[7] Li, P., Vrabie, D., Li, D., Bengea, S., Mijanovic, S., and O’Neill, Z. (2015). “Simulation and experimental demonstration of model predictive control in a building HVAC system.” Science and Technology for the Built Environment, 21(6), 721-732.

[8] Kim, D., and Braun, J. (2018). “Development, implementation and performance of a model predictive controller for packaged air conditioners in small and medium-sized commercial building applications.” Energy and Buildings, 178, 49-60.

[9] Vrettos, E., Kara, E. C., MacDonald, J., Andersson, G., and Callaway, D. S. (2018). “Experimental Demonstration of Frequency Regulation by Commercial Buildings—Part II: Results and Performance Evaluation.” IEEE Transactions on Smart Grid, 9(4), 3224-3234.

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget:
FY20: $250k each LBNL, PNNL, NREL, $125k ORNL
FY21: $250k each PNNL, NREL, $150k LBNL, $125k ORNL
FY22 (planned): $250k each PNNL, NREL, $150k LBNL, $100k ORNL

Variances: Originally planned for $250k in FY21,FY22 for LBNL but sufficient carry-over from FY20. Project plan not modified.

Cost to Date: $1.65 mil FY20-FY21

***Additional Funding**: No direct, leverage contributions from 13 partnering institutions in IBPSA Project 1.

Budget History					
10/1/2019– FY 2020 (past)		FY 2021 (current)		FY 2022 – 9/30/2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$875k	$0*	$775k	$0*	$750k	$0*

Project Plan and Schedule

Start Date: 10/1/2019, End Date: 9/30/2022	FY20				FY21				FY22			
Milestone Name (Lead Lab)	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work (**M** = milestone completed, **M** = originally planned, **G** = Go/No-Go)												
M2.2.1 KPI specification posted to github (PNNL)	M											
M2.3 Test scenarios and methods documentation completed (PNNL)		M										
M2.4.1 Calibration metrics identified (ORNL)		M										
M1.1 Software demonstration with example controller (NREL)		M										
M2.2.2 Automated KPI calculation implemented in software (LBNL)		M										
M4.2.1 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)		M										
M2.1.1 Large office testcase completed (PNNL)			M									
M1.2 Automated test procedure and KPI report for a test controller (NREL)				M								
M3.1.1 Full repository of test cases baseline benchmarked (PNNL)				M								
M2.5.1 Test case repository version release on github (LBNL) (Go/No-Go)				G								
M4.2.2 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)				M								
M1.4 Continuous integration testing (NREL)					M							
M2.1.2 Medium office test case completed (LBNL)					M	M						
M2.1.3 Initial FRP test case developed (ORNL)						M						
M3.2.1 At least one repository test case benchmarked with MPC controller (PNNL)						M						
M4.2.3 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)						M						
M3.2.2 At least one repository test case benchmarked with Modified MPC controller (PNNL)							M					
M3.2. At least one repository test case benchmarked with ACS controller (LBNL)							M					
Updates to BOPTEST Service and BOPTEST Dasboard published on GitHub (NREL)							M					
M1.5.1 BOPTEST Software Version Release (LBNL) (Go/No-Go)							G					
Future Work												
M2.5.2 Test Case Repository Version Release (LBNL)								M				
M4.3.1 Workshop Held (LBNL)								M				
M1.3.2 Prototype API for interacting with control and sensor point metadata (NREL)								M				
M4.2.4 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)								M				
M3.1.2 Full repository of test cases baseline benchmarked (PNNL)								M				
M2.4.2 FRP test case calibrated (ORNL)									M			
M2.1.4 Single zone office test case completed (LBNL)									M			
M4.2.5 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)										M		
M2.1.5 Large office and power grid tool test case completed (PNNL)											M	
M4.3.2 Hackathon held (LBNL)											M	
M1.5.2 BOPTEST Software version release on github (LBNL)											M	
M1.6.1 BOPTEST-Service Available Online (NREL)											M	
M3.1.3 Full repository of test cases baseline benchmarked (PNNL)												M
M2.5.3 Test case repository version release on github (LBNL)												M
M4.2.6 Bi-annual TAG meetings held, Q2 and Q4 each FY (LBNL)												M