IBPSA Project 2: BOPTEST
Introduction and Project Status

IBPSA Project 2

Expert Meeting
Denver, CO

May 22, 2024

Co-Operating Agents:

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IBPSA Project 2: BOPTEST
Introduction and Project Status

Thank you to IBPSA USA for room availability

IBPSA Project 2: BOPTEST
Introduction and Project Status

- BOPTEST
    - Motivation and Concept
    - Technical Approach and Example Usage
- Project 2
    - Objectives, Tasks, and Registration Stats
    - Ongoing Efforts

Motivation

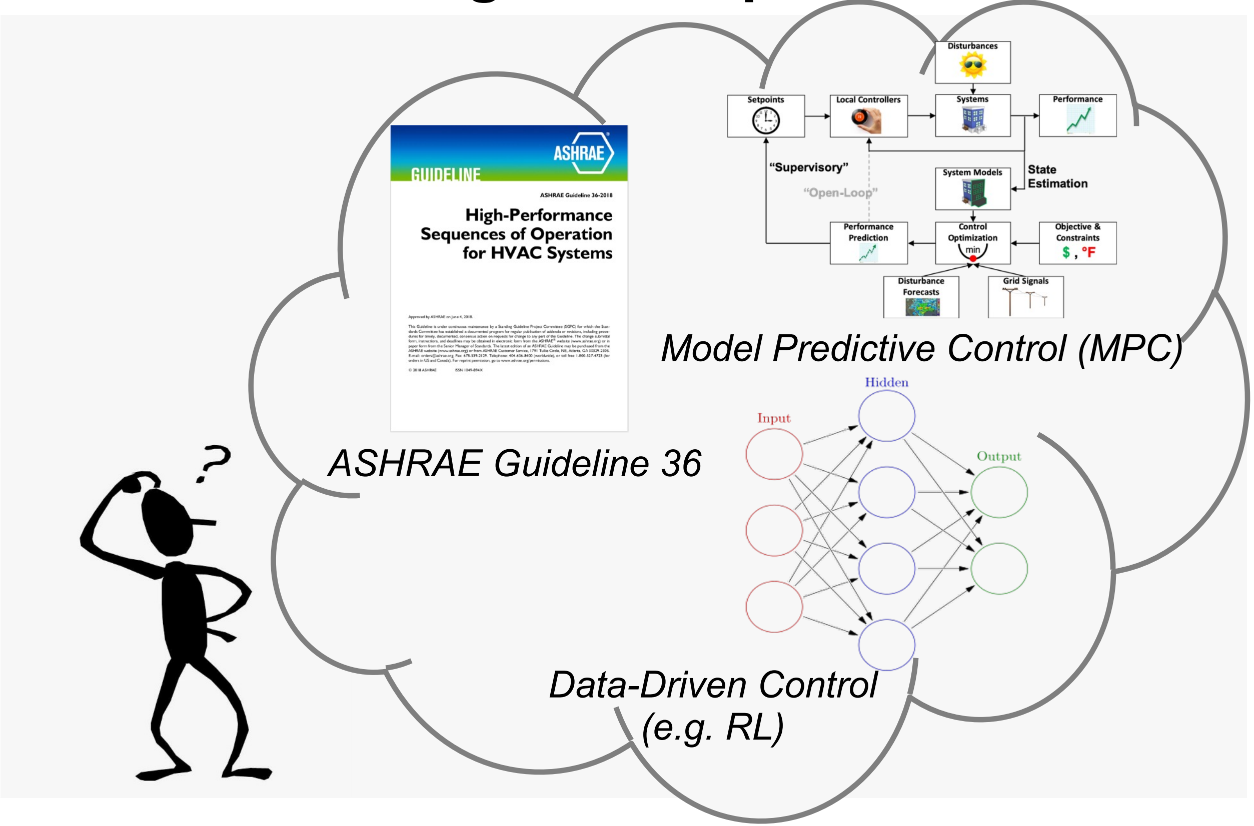
Many new and advanced control strategies hold promise …

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

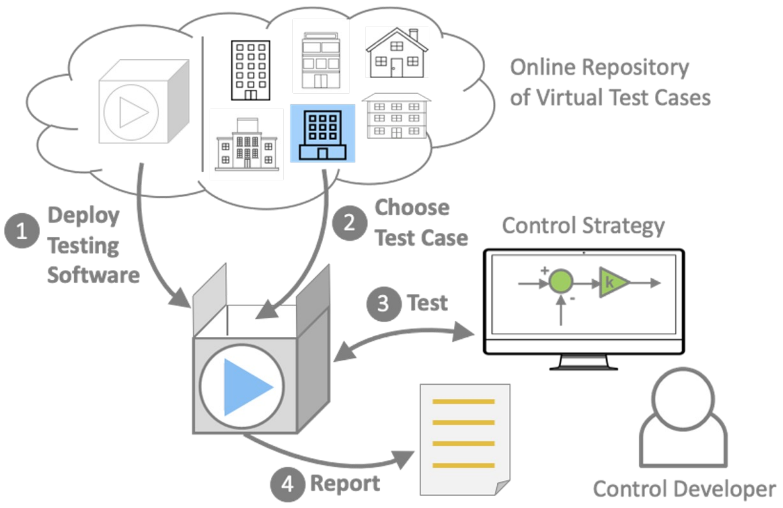


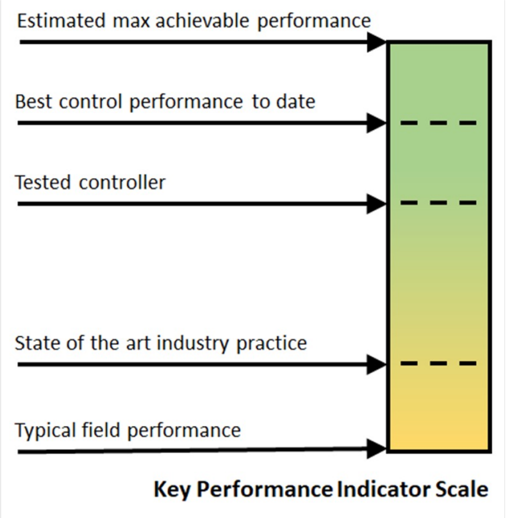
Concept

Building Optimization Testing Framework (BOPTEST)

A Simulation-Based Controls Testing and Benchmarking Environment

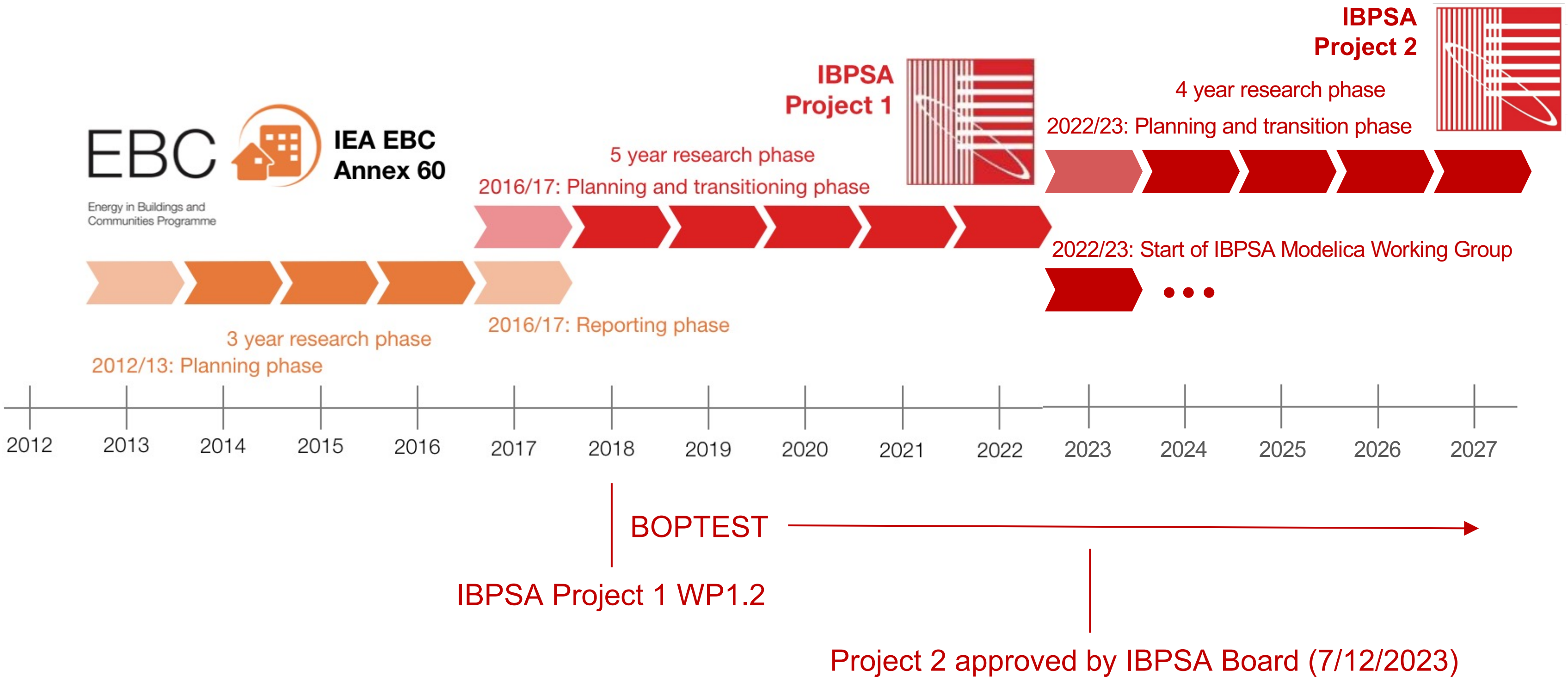
- Deployable software runtime environment: rapidly, repeatably, and at scale
- Control-interactive high-fidelity emulator models with defined boundary conditions
- Standardized key performance indicators (KPI) that are auto-calculated





History

- Extending 10 years of international collaboration on Modelica and FMI-based modeling for building and urban energy system design and operation



Community Development:

Institution	Team
Arup, Australia, USA, UK	Haico Schepers, Raffe Brennan, Robert Knight
Builtwins, Belgium	Filip Jorissen, Lieve Helsen
dnergy, Belgium	Roel De Coninck, Bart Merema, Iago Cupeiro,
Devetry, USA	Chris Berger, Philip Gonzalez, Amit Kapoor
ENGIE, France	Valentin Gavan
ETH Zurich, Switzerland	Esther Borkowski, Felix Bunning
Hong Kong University of Science and Technology, Hong Kong	Zhe Wang, Wanfu Zheng
Johnson Controls, USA	Erik Paulson (formerly)
KU Leuven, Belgium	Lieve Helsen
Lawrence Berkeley National Laboratory, USA	David Blum, Michael Wetter, Ettore Zanetti
National Renewable Energy Laboratory, USA	Kyle Benne, Nicholas Long, Marjorie Schott, Tim Coleman, Jermy Thomas, Dave Biagioni, Yanfei Li
National University Singapore, Singapore	Sicheng (James) Zhan
Oak Ridge National Laboratory, USA	Yeonjin Bae, Piljae Im, Sen Huang
Pacific Northwest National Laboratory, USA	Yan Chen, Draguna Vrabie, Xing Lu, Jan Drgona, Robert Lutes
Politecnico di Torino, Italy	Davide Fop, Alfonso Capozzoli
Pure Control, France	Gauthier-Clerc Francois
R2M Solutions, Spain	Laura Zabala, Jesus Febres
RWTH Aachen, Germany	Laura Maier
SINTEF, Norway	Harald Walnum
Southern Denmark University, Denmark	Krzysztof Arendt, Christian Veje, Tao Yang
Technical University of Denmark, Denmark	Peder Bacher, Konstantin Filonenko
WEDOCO, Belgium	Javier Arroyo

Approach

Building Optimization Testing Framework (BOPTEST)

A Simulation-Based Controls Testing and Benchmarking Environment

- Deployable software runtime environment: rapidly, repeatably, and at scale
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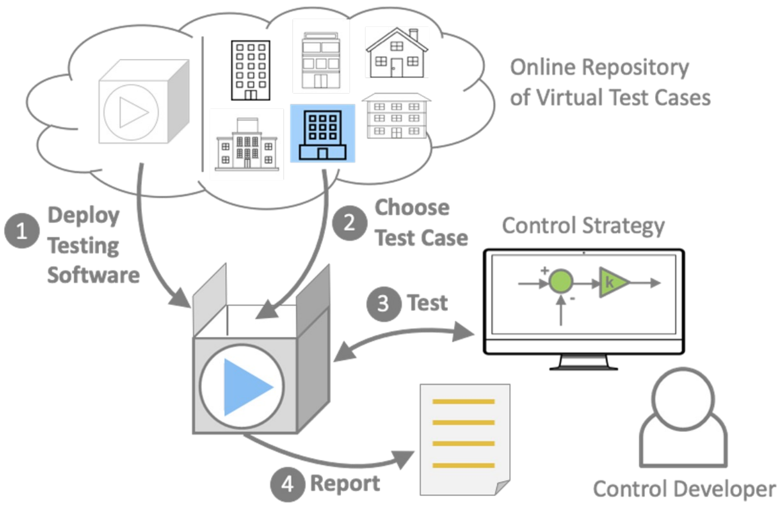
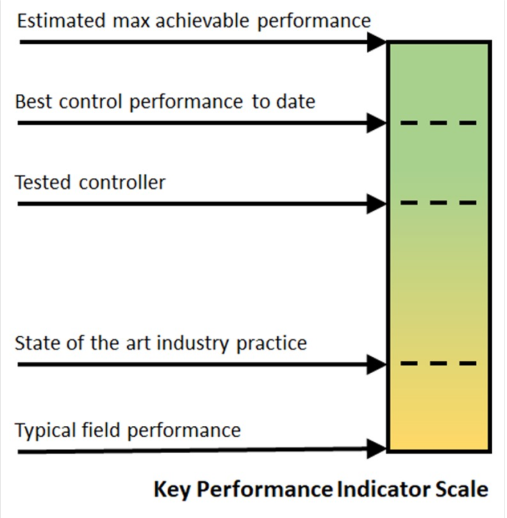
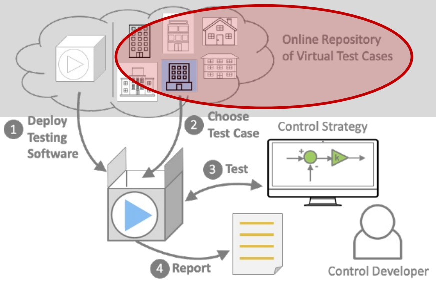


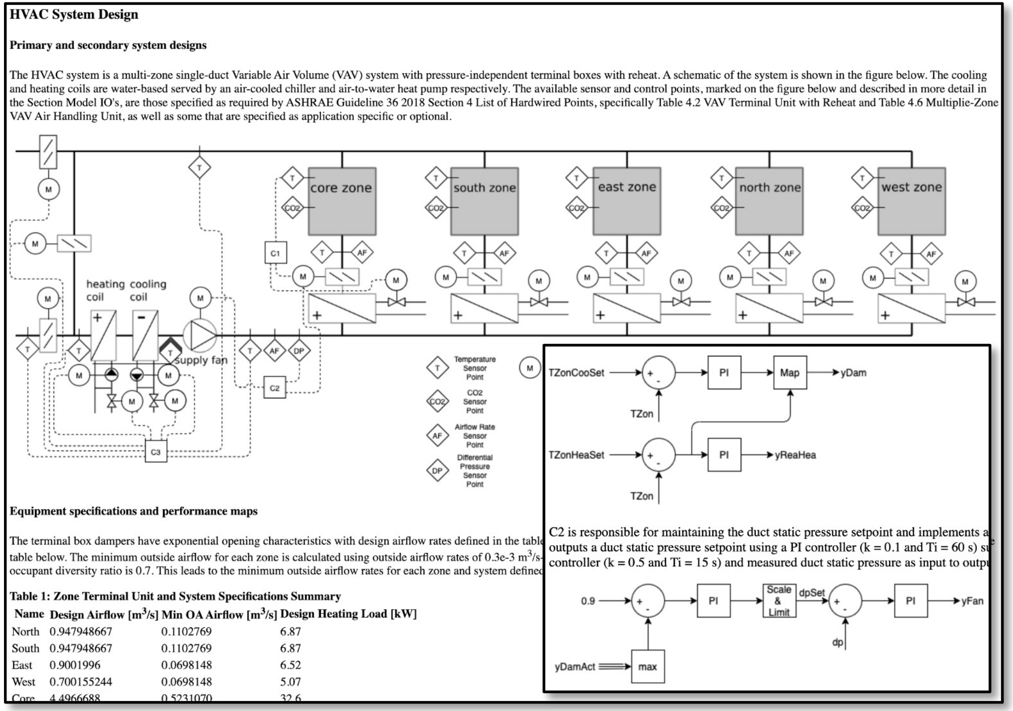


Approach

Building Emulators ("Test Cases")

- High-fidelity models with embedded baseline control in Modelica, Spawn, and CDL, exported as FMU
- 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 Multiple-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 m^3/s- occupant diversity ratio is 0.7. This leads to the minimum outside airflow rates for each zone and system defined

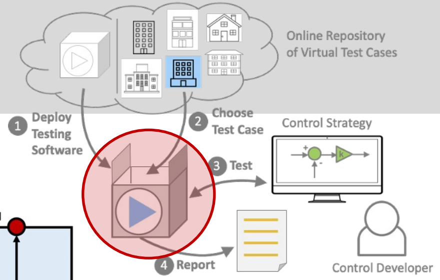
C2 is responsible for maintaining the duct static pressure setpoint and implements a outputs a duct static pressure setpoint using a PI controller (k = 0.1 and Ti = 60 s) s controller (k = 0.5 and Ti = 15 s) and measured duct static pressure as input to outpu

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

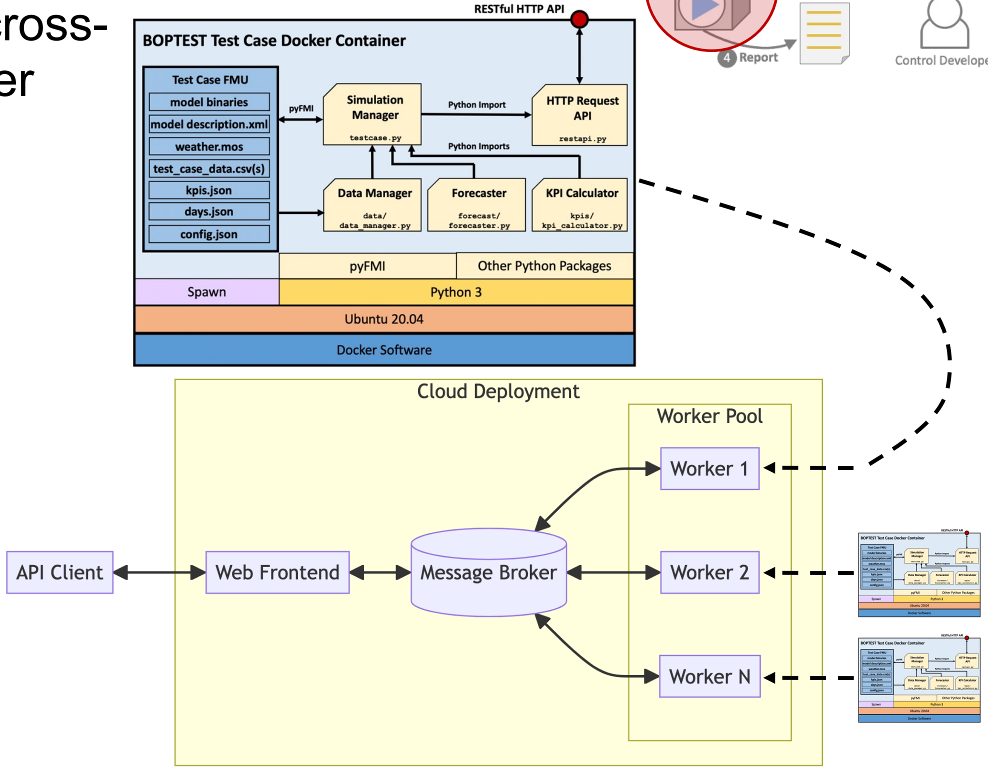


Run-Time Environment

- Rapid, repeatable deployment locally cross-platform or as web-service using Docker
- ”Native” HTTP RESTful API for test management and controller interaction

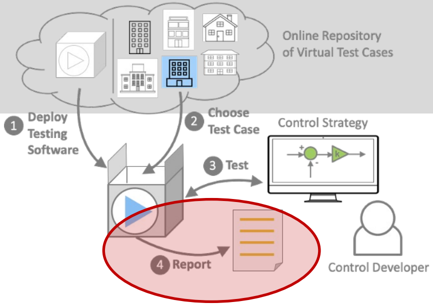
API Endpoint	Description
GET *measurements*	Receive available measurement points
GET *inputs*	Receive available input points
PUT *scenario*	Set test scenario (time period, ele. price)
PUT *initialize*	Initialize simulation
PUT *step*	Set control step
GET *forecast*	Receive forecasts
POST *advance*	Advance simulation with control input
PUT *results*	Receive historic point trajectory
GET *kpi*	Receive KPI values
POST *submit*	Submit results to online dashboard

HTTP RESTful API Summary



Web-Service deployment architecture based on version of Alfalfa Virtual Building Service at https://github.com/NREL/boptest-service

Approach

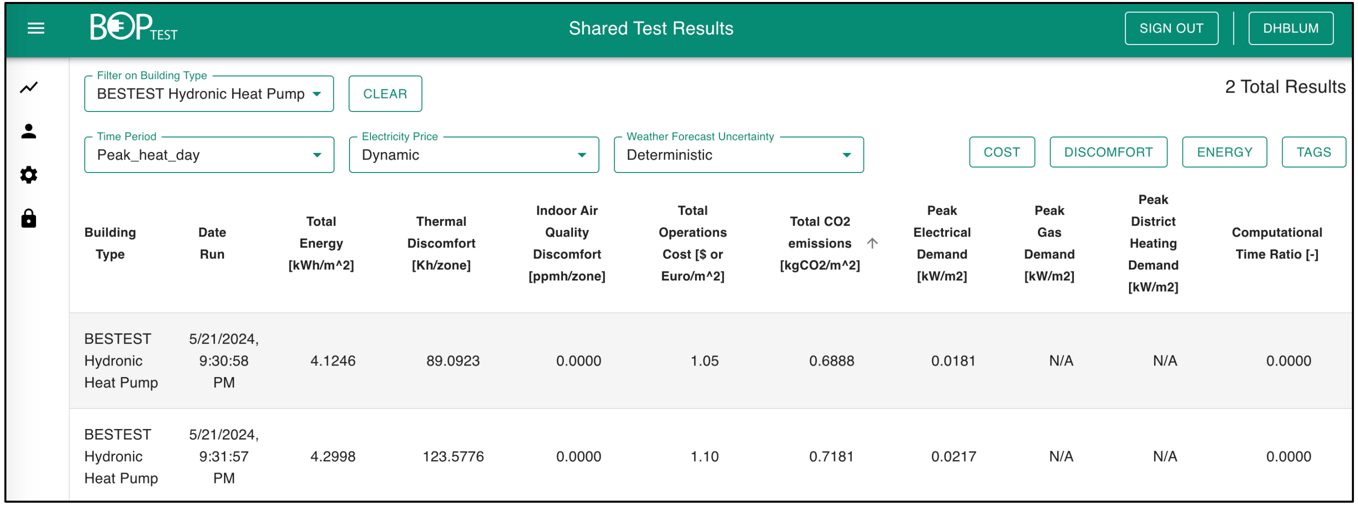


Evaluation Design

- 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 (coming soon)

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 Demand	kW / m^2
Computational Time Ratio	[-]

KPIs calculated by BOPTEST



Building Type	Date Run	Total Energy [kWh/m^2]	Thermal Discomfort [Kh/zone]	Indoor Air Quality Discomfort [ppmh/zone]	Total Operations Cost [$ or Euro/m^2]	Total CO2 emissions [kgCO2/m^2]	Peak Electrical Demand [kW/m2]	Peak Gas Demand [kW/m2]	Peak District Heating Demand [kW/m2]	Computational Time Ratio [-]
BESTEST Hydronic Heat Pump	5/21/2024, 9:30:58 PM	4.1246	89.0923	0.0000	1.05	0.6888	0.0181	N/A	N/A	0.0000
BESTEST Hydronic Heat Pump	5/21/2024, 9:31:57 PM	4.2998	123.5776	0.0000	1.10	0.7181	0.0217	N/A	N/A	0.0000

Online dashboard

Framework Status

- Home Page: https://boptest.net/
- BOPTEST v0.6.0 (April) for core framework software and test cases:
  - Repo: https://ibpsa.github.io/project1-boptest/
  - v0.5.0 Downloads (Oct 23 – Mar 24): 147
  - GitHub: 99 Stars, 64 Forks
- BOPTEST-Service v0.4.0 (April) supporting BOPTEST v0.6.0:
  - Public API: https://api.boptest.net
  - Repo: https://github.com/NREL/boptest-service
- Gym environment interface with support for v0.6.0 (May): https://github.com/ibpsa/project1-boptest-gym
- Updated Online Results Dashboard coming soon to https://dashboard.boptest.net/
- Join the google group: https://groups.google.com/g/ibpsa-boptest

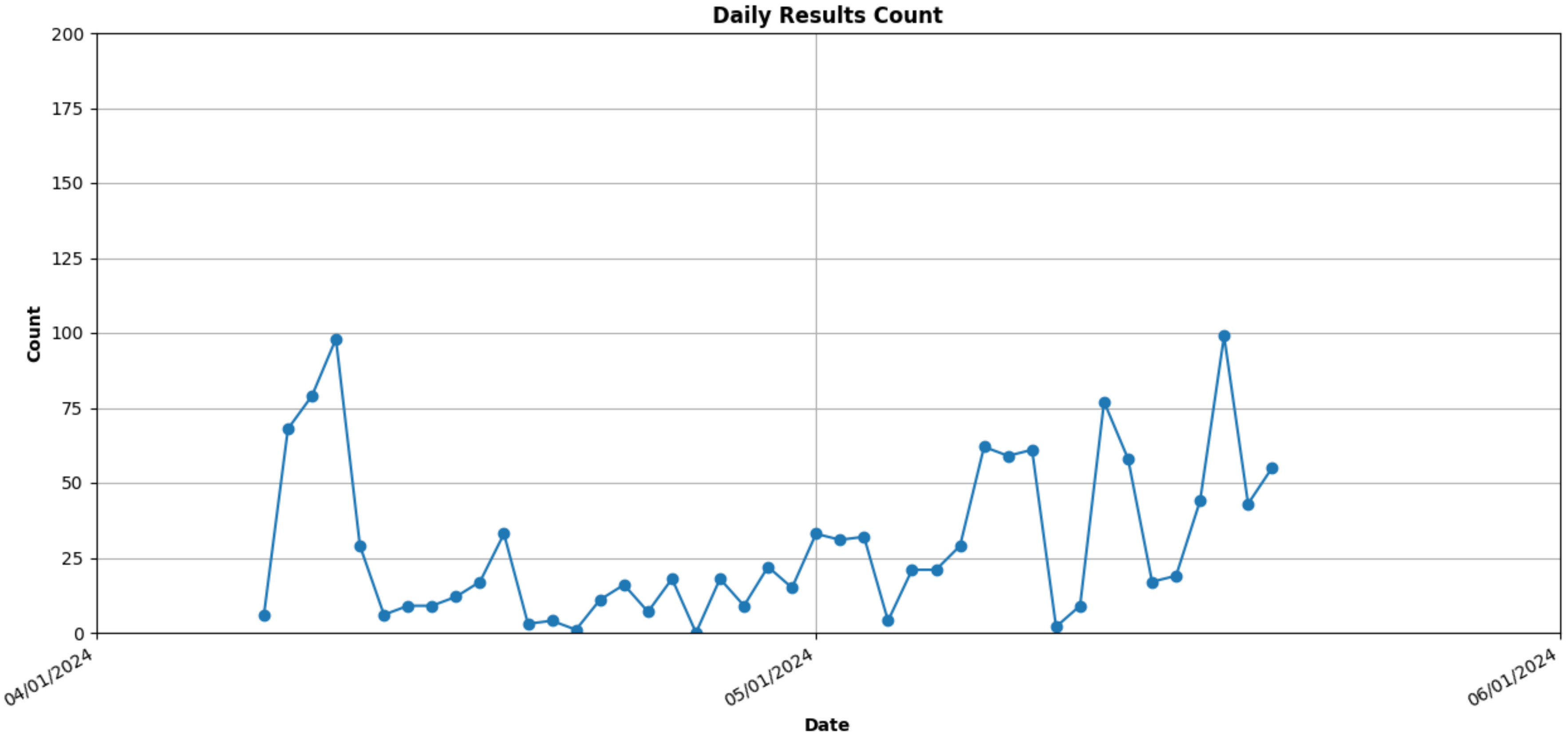
Hydronic	Air
Single zone + Radiator *"bestest_hydronic"*	Single zone + FCU *"bestest_air"*
Single zone + Floor heat and heat pump *"bestest_hydronic_heat_pump"*	Single zone + RTU with DX, gas furnace
2 zone + Floor heat and heat pump *"twozone_apartment_hydronic"*	2 zone + FCUs + AHUs with gas boiler, chiller *"multizone_commercial_simple_hydronic"*
Single zone class + Radiator, AHU, CO2 control *"singlezone_commercial_hydronic"*	5-Zone + 1 VAV AHU with reheat with chiller and heat pump "multizone_commercial_simple_air"
8-Zone + Radiators, boiler, and split cooling *"multizone_residential_hydronic"*	10-zone + 1 VAV RTU with reheat, DX, electric heating *"flexible_research_platform"*
	15-Zone + 3 VAV AHU with reheat, chiller, boiler *"multizone_commercial_complex_air"*

Available   *Implemented, but not yet available*

Test case development progress within IBPSA Project 2

Framework Usage

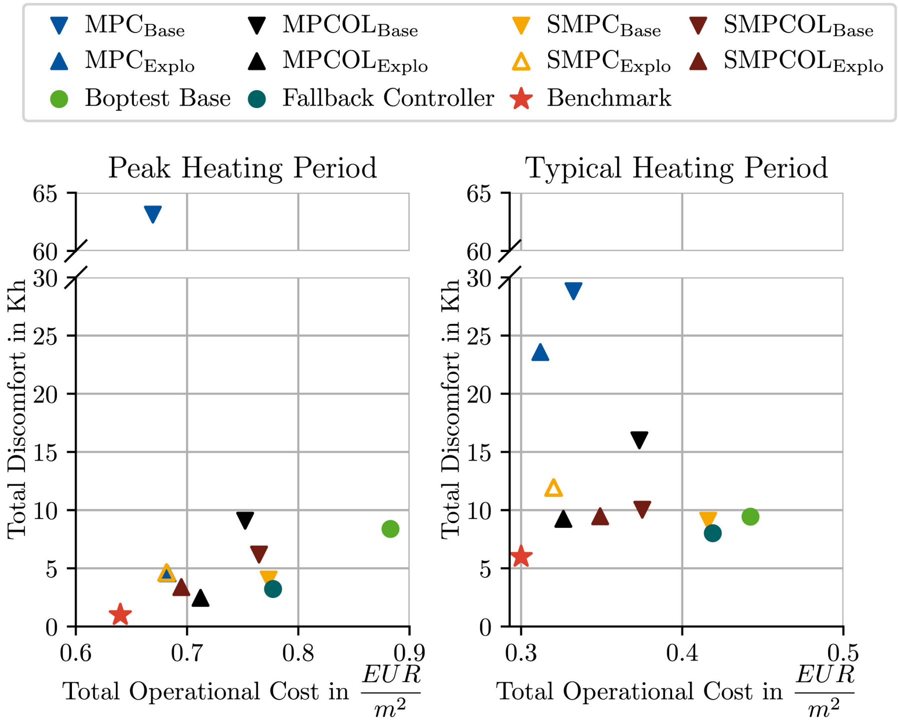
Public Web-Service Usage (number of results created per day)



Framework Usage

Recent Research Examples

- Safe operation of online learning data driven model predictive control of building energy systems
  (Stoffel et al. 2024: https://doi.org/10.1016/j.egyai.2023.100296)
- Simulation-based assessment of ASHRAE Guideline 36, considering energy performance, indoor air quality, and control stability
  (Faulkner et al. 2023: https://doi.org/10.1016/j.buildenv.2023.110371)
- Enabling portable demand flexibility control applications in virtual and real buildings
  (Pereira et al. 2024: https://doi.org/10.1016/j.jobe.2024.108645)



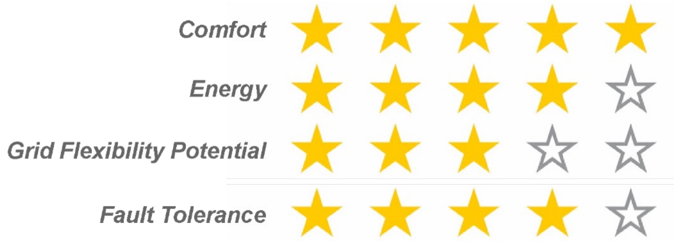
"Fig. 8. Control performance results of the BOPTEST scenarios for the examined setups. The benchmark controller is a physics-based MPC from Arroyo et al. 2022 (https://doi.org/10.3389/fbuil.2022.849754) for comparison." *(Under Creative Commons License From Stoffel et al. 2024 – link at left).*

Framework Usage

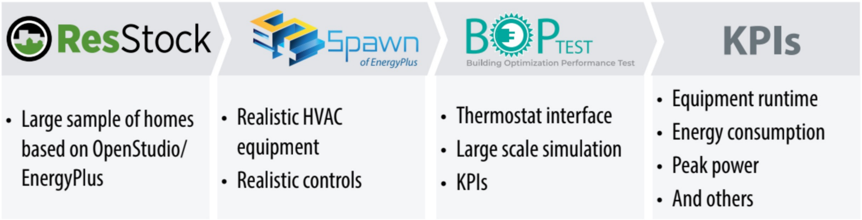
Industry Examples

dnergy (Belgium), **Edo Energy** (USA)
Maturing MPC control solutions before deployment

ARUP (Australia, USA, UK)
Developing workflow to provide building owners comparative performance evaluations for advanced controls



EPA EnergyStar (USA)
Evaluating Smart Thermostat performance
Benne et al. 2024 “Simulation Driven Rating of Smart Thermostats”, IBPSA USA SimBuild 2024



Prototyped workflow for thermostat benchmarking (Benne 2023 https://www.energy.gov/sites/default/files/2023-05/bto-peer-2023-32620-benchmarkingthermostats-nrel-benne.pdf)

ADRENALINE (Led by Norway)
Smart Building HVAC Control Challenge open competition
https://adrenalin.energy/adrenalin-2023-smart-building-hvac-control-challenge

Project 2 Objectives

IBPSA Project 2

- Continue open-source (BSD) development of BOPTEST software infrastructure, emulators, and related extensions to meet the growing needs of building and urban energy system controls development and evaluation worldwide.
- Use BOPTEST to evaluate and benchmark advanced control strategies.
- Build an international community around the advancement of controls in building and urban energy systems.

Project 2 Tasks and Leadership

Co-Operating Agents: David Blum, LBNL and Lieve Helsen, KU Leuven - EnergyVille

1. **Task 1: Outreach and Community Building**
   Lead: Javier Arroyo, WEDOCO, Spain

   Activities that encourage, facilitate, and disseminate BOPTEST usage, adoption, and feedback to development. Including workshops, tutorials, website maintenance, usage and case study collection.

2. **Task 2: Methods and Infrastructure**
   Lead: David Blum, LBNL, USA

   Development and maintenance of core software and closely related extensions. Including architecture, FMU simulation and data management, scenario definition, KPI calculation, forecast delivery, API, dashboard, web-service, and interfaces.

3. **Task 3: Test Cases**
   Lead: Ettore Zanetti, LBNL, USA

   Development and maintenance of benchmark emulators, so-called “test cases.” Continue to utilize the Modelica language and Functional Mockup Interface (FMI) standard, particularly open-source libraries that extend from Modelica IBPSA Library.

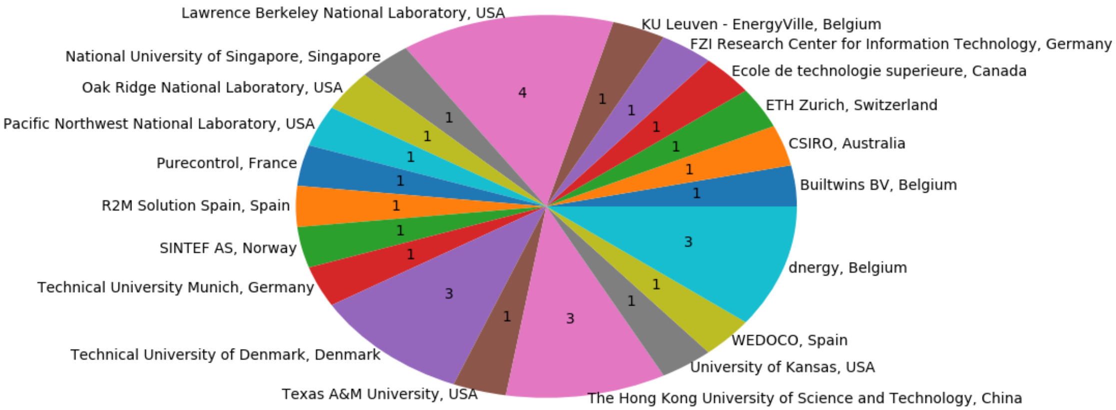
4. **Task 4: Controller Testing**
   Co-leads: Esther Borkowski, ETH Zurich, Switzerland & Zhe Wang, HKUST, Hong Kong

   Testing, benchmarking, and comparing control strategies by Project participants.

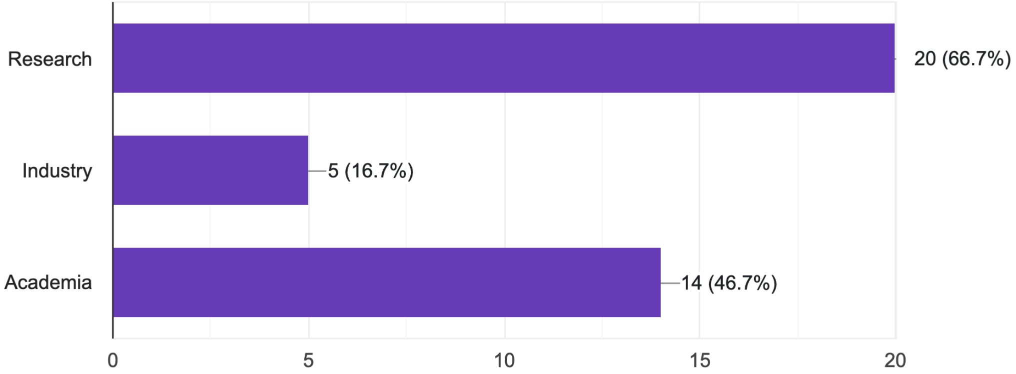
Project 2 Participation

As of May 20, 2024:
(registered using google form)

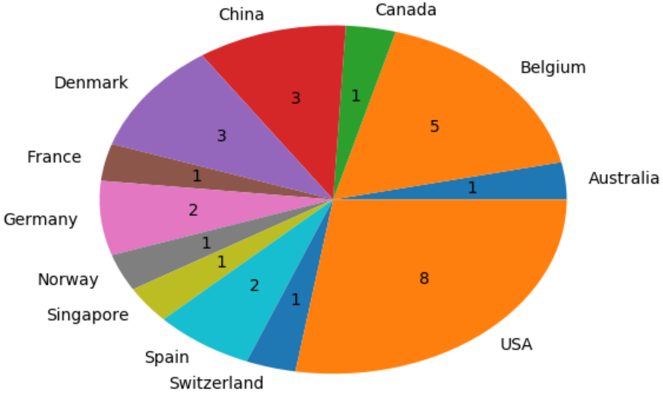
- 29 Registrants
- 20 Organizations
- 12 Countries



Breakdown by Organization



Breakdown by Organization Type



Breakdown by Country

Project 2 Participation

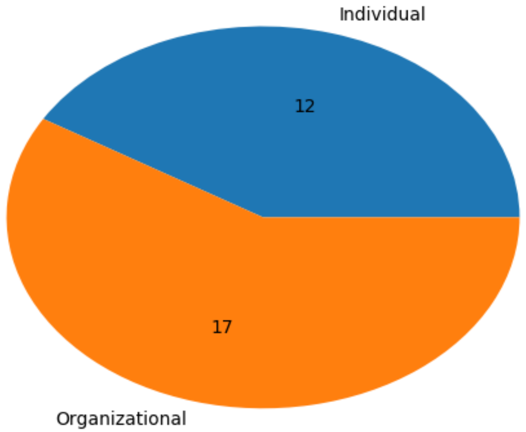
As of May 20, 2024:
(registered using google form)

- 29 Registrants

Organizational: Organizations that commit to contribute a minimum of 6 months FTE per project year using their own funding, contribute to 5-10 virtual meetings annually, and attend two-day semi-annual expert meetings using their own funding.

Individual: Contributors that participate as is custom in other open-source projects without a predetermined level of commitment.

Sponsor: Participants or organizations that fund the Project with cash contribution at US-$ 5,000 per year. Go to items such as expenses for in-person expert meetings (i.e. rooms, food, A/V, and student travel scholarship) and CI testing.



Project 2 Contribution Interest

As of May 20, 2024:
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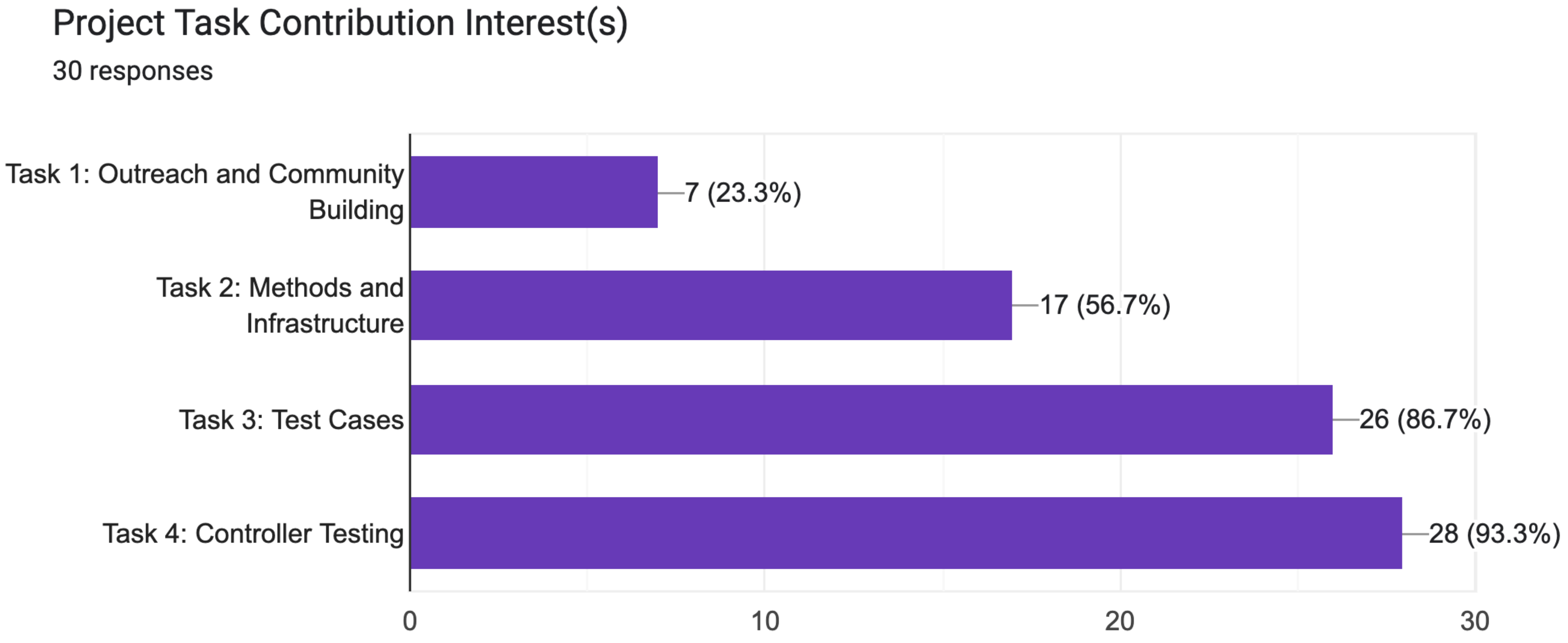

Project 2 Ongoing Efforts

Task 1: Outreach and Community Building

- Workshop in May at Seville University to teach BOPTEST and BOPTEST-Gym (WEDOCO)
- Climate Change AI Summer School June-August will include BOPTEST and BOPTEST-Gym tutorials (WEDOCO)
- Presentations at IBPSA USA SimBuild 2024 (LBNL, PNNL, NREL)
- Possibility of contest run by Project 2

Project 2 Ongoing Efforts

Task 2: Methods and Infrastructure

- Weather forecast uncertainty (R2M, HKUST)
- Repository refactor and Alfalfa alignment (LBNL, NREL)
- Online dashboard (NREL)
- DOPTEST (KU Leuven, LBNL)
- OpenModelica test case compilation testing (LBNL)
- Semantic models (LBNL)
- New KPI – Actuator Travel (PNNL, TUM, LBNL)

Project 2 Ongoing Efforts

Task 3: Test Cases

- New: Multizone Office Hydronic Simple (dnergy)
- New: Multizone Office Air Complex (PNNL)
- New: Flexible Research Platform (ORNL)
- New: DOPTEST (KU Leuven)
- Update: Two Zone Apartment Hydronic (LBNL, RWTH Aachen)
- Update: Single Zone Commercial Hydronic (SINTEF)
- New emulator proposals (DTU, ÉTS)
- Revision to Peer Review document and process (LBNL)

Project 2 Ongoing Efforts

Task 4: Controller Testing

- Proposal to organize workshops and seminars for BOPTEST users to share usage and insights on controller performance (ETH, HKUST)
- Benchmark performance of ASHRAE Guideline 36 and MPC on Multizone Office Air Complex test case (PNNL)

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IBPSA Project 2

Thank you!

BOPTEST Home Page: https://boptest.net

IBPSA Project 2: https://ibpsa.github.io/project1-boptest/ibpsa/index.html

Join the mailing list: https://groups.google.com/g/ibpsa-boptest

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