IBPSA Project 2: BOPTEST

Introduction and Project Status

IBPSA Project 2

Expert Meeting
DTU, Denmark

November 20, 2024

Co-Operating Agents:

David Blum
Computational Research Scientist/Engineer
Building Technology and Urban Systems Division
Lawrence Berkeley National Laboratory (LBNL)
Email: dhblum@lbl.gov

Lieve Helsen
Professor
Department of Mechanical Engineering
KU Leuven
Email: lieve.helsen@kuleuven.be

IBPSA Project 2: BOPTEST

Introduction and Project Status

Thank you to Matthias Van Hove and Peder Bacher
and to all DTU staff for hosting!

IBPSA Project 2: BOPTEST

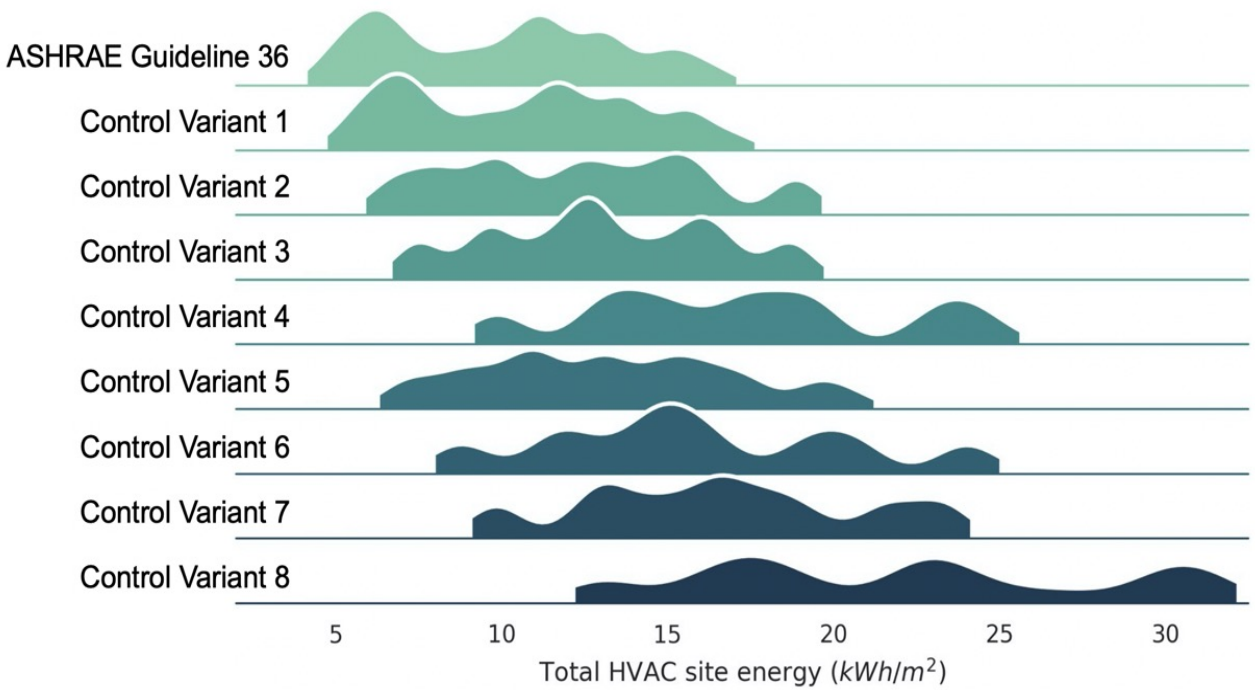
Introduction and Project Status

- **BOPTEST**
  - Motivation and Concept
  - Technical Approach
  - Recent Example Usage
- **Project 2**
  - Objectives, History, and Structure
  - Participation
  - Philosophical Aims

Motivation

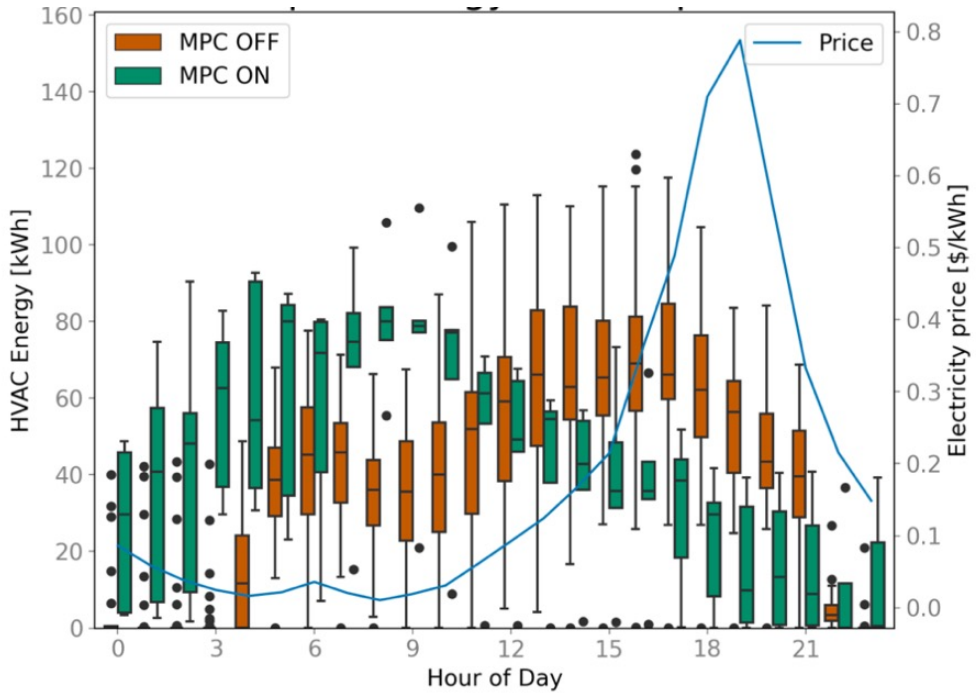
Control Performance Matters

Energy Efficiency



Histograms for nine control variants of simulated HVAC energy for a 21-zone VAV system among varying operating conditions, 243 cases [1].

Grid-Integrated, Load Flexibility



Hourly HVAC energy for price-responsive Model Predictive Control (MPC) in a real commercial building at LBNL in 2023 [2].

[1] Zhang et al. (2022). "Estimating ASHRAE Guideline 36 energy savings for multi-zone variable air volume systems using Spawn of EnergyPlus." *J. of Building Performance Simulation*. https://doi.org/10.1080/19401493.2021.2021286.

[2] Zanetti et al. (2024). "Field Performance of Commercial Building Load Flexibility Using Model Predictive Control." In *Proc. of the 8th International High Performance Buildings Conference at Purdue*, Contribution 3216. https://engineering.purdue.edu/Herrick/about/news/Conferences/2024/Documents.

Motivation

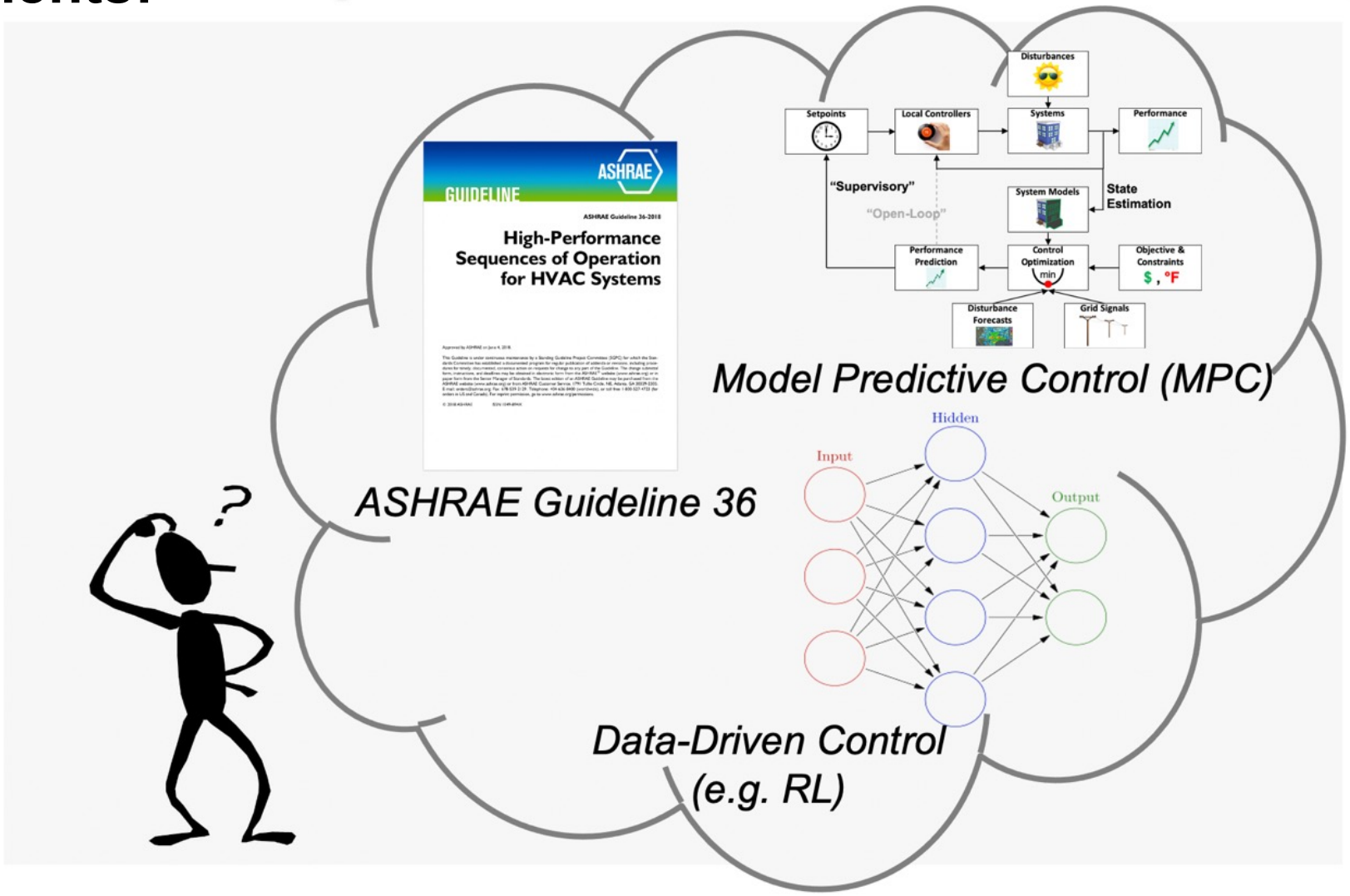
There Are Many New Control Strategies

All have different requirements:

- Data
- Modeling
- Computation
- Expertise

How do they compare?

- Thermal comfort
- Energy management
- Implementation cost
- Reliability



Motivation

Current Approach: Individualized Case Studies

- Findings are specific to building, climate, metrics, comparative baseline
- Difficult to replicate and extend to new control strategies in future studies
- Effort and expertise to set up case study limits rapid prototyping and development by experts in fields outside traditional building industry

Comparative evaluation accelerates new control deployments

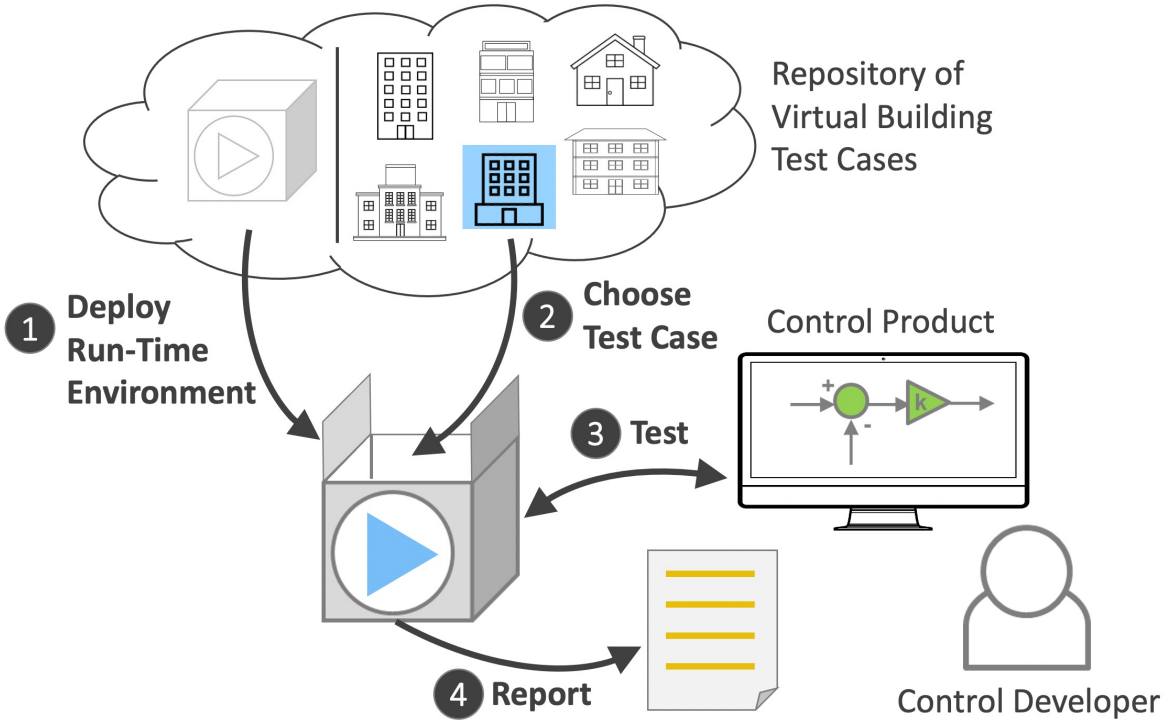
- **Control developers** streamline new control development and deployment
- **Building owners** identify value among new and existing products
- **Policy makers** establish performance expectations and incentive programs
- **Educators** train students on performance expectations and commissioning

Concept

Building Optimization Testing Framework (BOPTEST)

A Simulation-Based Controls Testing and Benchmarking Environment

- Realistic virtual buildings that can be controlled by external test controllers
- Deployable software runtime environment: rapidly, repeatably, and at scale
- Standardized key performance indicators (KPI) that are auto-calculated



Novelties

Provides a level playing field for control performance comparison.

Lowers the barrier for access to realistic building simulations.

Creates an international, open community for controls testing and benchmarking.

Approach

Virtual Building Models ("Test Cases")

- High-fidelity models with embedded baseline control in Modelica, Spawn, and ASHRAE 231p (CDL)
- Overwritable supervisory or local-loop control
- All boundary condition data (e.g. weather, schedules, electricity prices, CO2 factors)
- Documentation and peer review to ensure quality and usability
- Semantic models (in-progress)

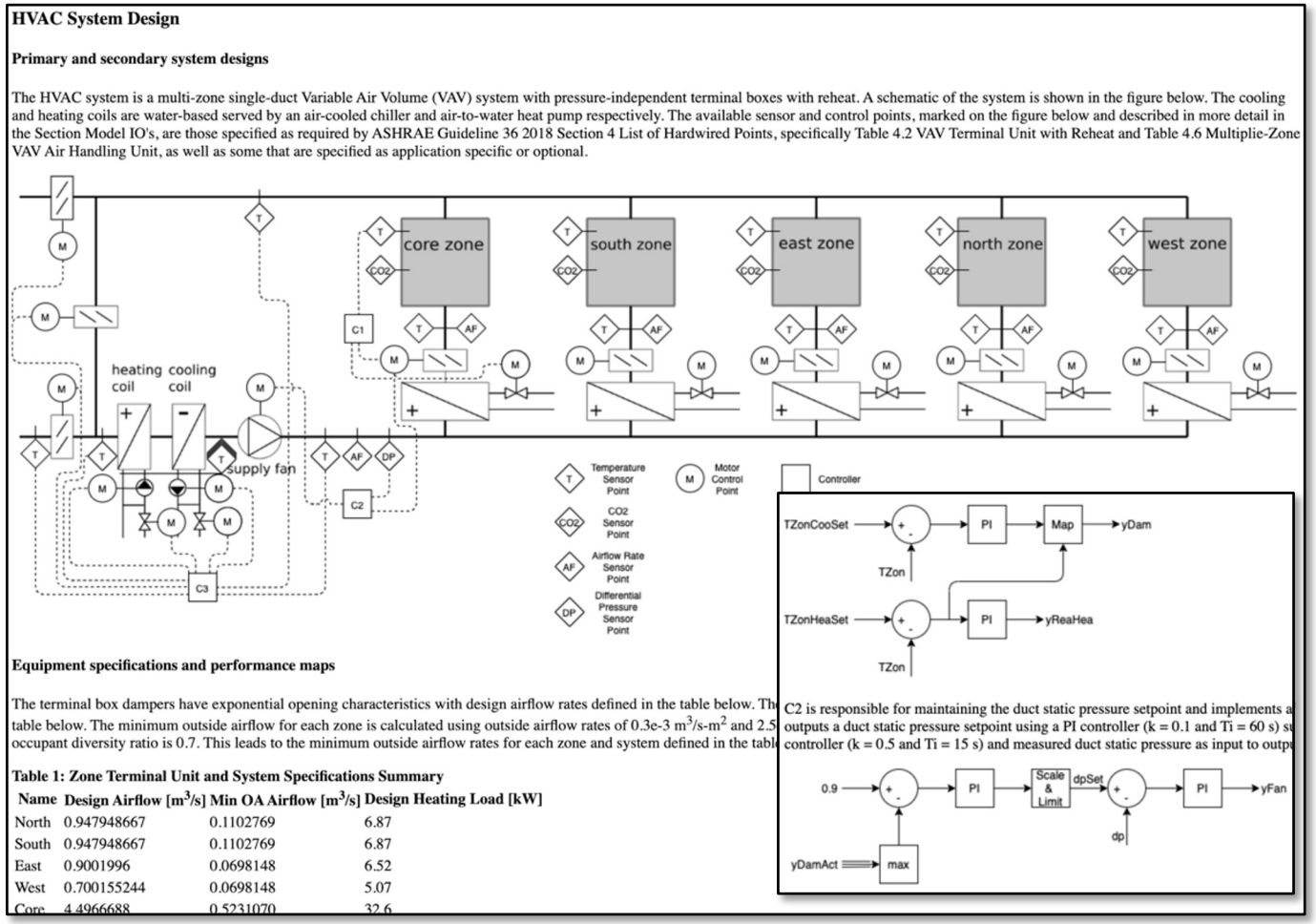
Modelica Association

fmi Functional Mock-up Interface

Application Libraries of

modelica-ibpsa

https://github.com/ibpsa/modelica-ibpsa



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 below. The table below. The minimum outside airflow for each zone is calculated using outside airflow rates of 0.3e-3 $m^3/s\text{-}m^2$ and 2.5 occupant diversity ratio is 0.7. This leads to the minimum outside airflow rates for each zone and system defined in the tabl

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) su controller (k = 0.5 and Ti = 15 s) and measured duct static pressure as input to outpu

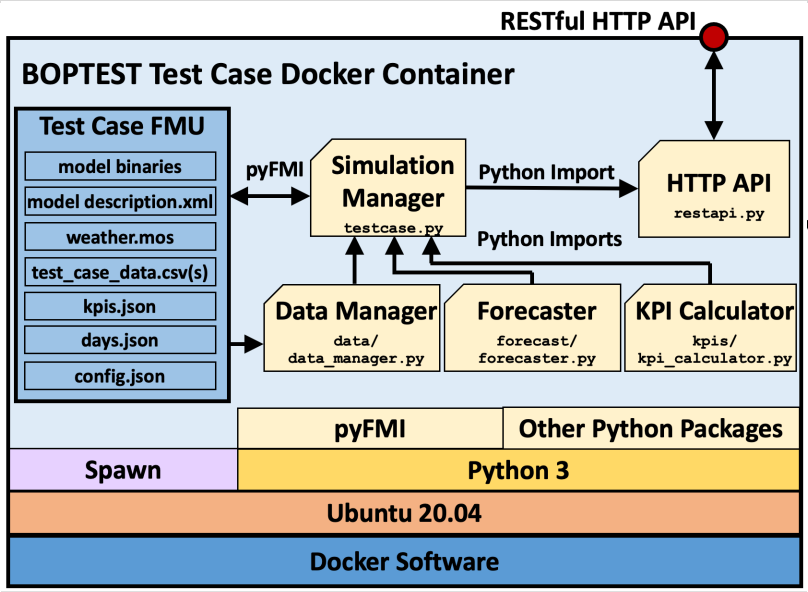
Table 1: Zone Terminal Unit and System Specifications Summary

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

Approach

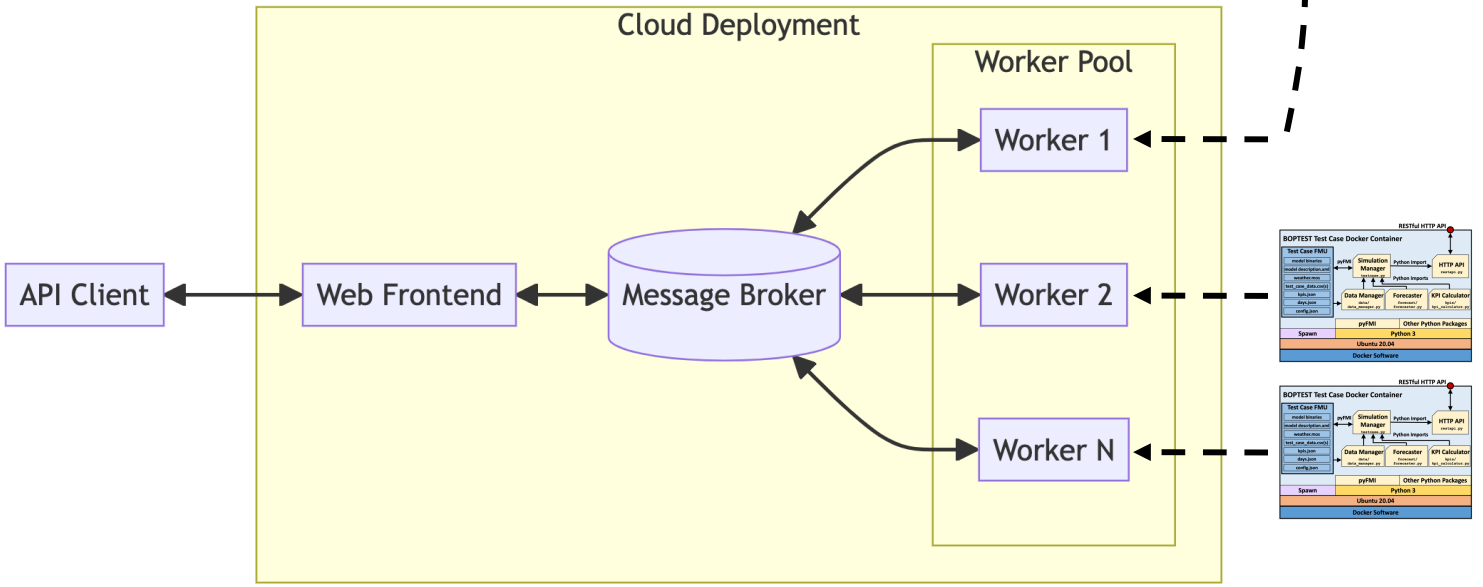
Run-Time Environment

- Rapid, repeatable deployment as a web-service using Docker
- “Native” HTTP RESTful API for test management and controller interaction



API Endpoint	Description
GET *measurements*	Receive available measurements
GET *inputs*	Receive available inputs
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 API Requests



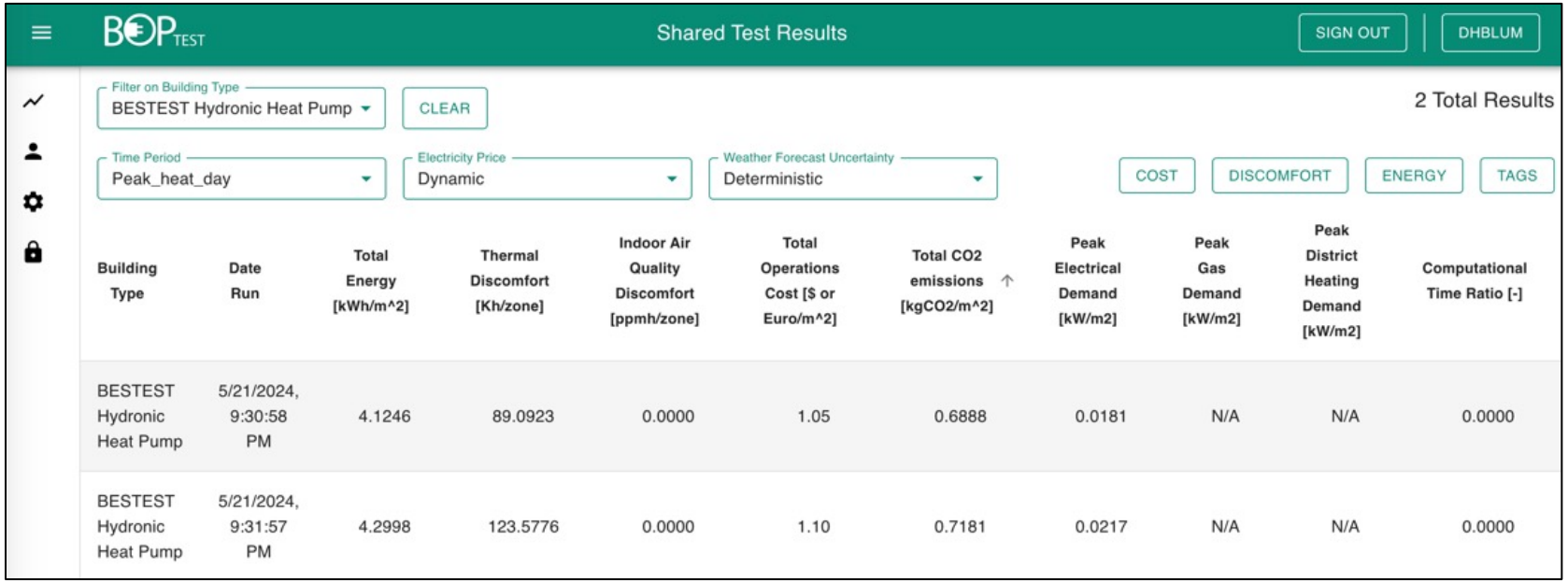
Web-service deployment architecture based on version of Alfalfa Virtual Building Service at https://github.com/NREL/boptest-service.

Approach

Test Design

- Set of KPIs calculated by framework
- Predefined test scenarios
  - Time period
  - Electricity price
- Online dashboard prototyped for registering users and collecting results
- Additional Interfaces
  - Gym
  - BACnet
  - VOLTTRON

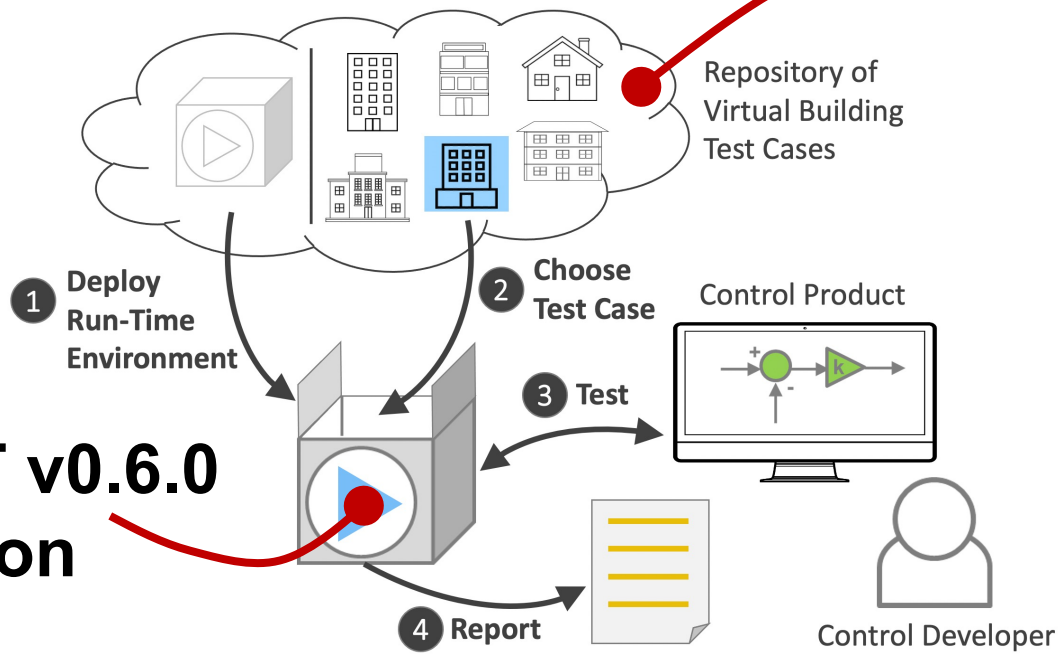
Description	Unit
Energy Use	kWh / m^2
Energy Cost	$ / m^2
Emissions	KgCO2 / m^2
Thermal Discomfort	K.h / zone
IAQ Discomfort	ppm.h / zone
Peak Elec/Gas/District Demand	kW / m^2
Computational Time Ratio	[-]



Approach

Progress

Home Page: https://boptest.net



BOPTEST v0.6.0 available on GitHub

Available as a public web-service by sending API requests to https://api.boptest.net

8 publicly available test cases

More under active development

Hydronic	Air
1 Zone, Radiator	1 Zone, FCU
1 Zone, Radiant Floor, Heat Pump	2 Zones, FCUs, AHUs Heat Pump, Chiller
2 Zones, Radiant Floor, Heat Pump	5 Zones, 1 VAV AHU, Heat Pump, Chiller
1 Zone, Radiator, AHU, CO_2 Control	10 Zones, 1 VAV RTU, DX, Ele. Heat
8 Zones, Radiators, Boiler, Split Cooling	15 Zones, 3 VAV AHUs, Boiler, Chiller

Available

Implemented, but not yet available

Approach

Progress

8 publicly available test cases

More under active development

Hydronic	Air
1 Zone, Radiator	1 Zone, FCU
1 Zone, Radiant Floor, Heat Pump	2 Zones, FCUs, AHUs Heat Pump, Chiller
2 Zones, Radiant Floor, Heat Pump	5 Zones, 1 VAV AHU, Heat Pump, Chiller
1 Zone, Radiator, AHU, CO_2 Control	10 Zones, 1 VAV RTU, DX, Ele. Heat
8 Zones, Radiators, Boiler, Split Cooling	15 Zones, 3 VAV AHUs, Boiler, Chiller

“bestest_ hydronic”

“bestest_hydronic_heat_pump”

“twozone_apartment_hydronic”

“singlezone_commercial_hydronic”

“multizone_residential_hydronic”

“bestest_air”

“multizone_office_simple_hydronic”

“multizone_office_simple_air”

“flexible_research_platform”

“multizone_office_complex_air”

Available

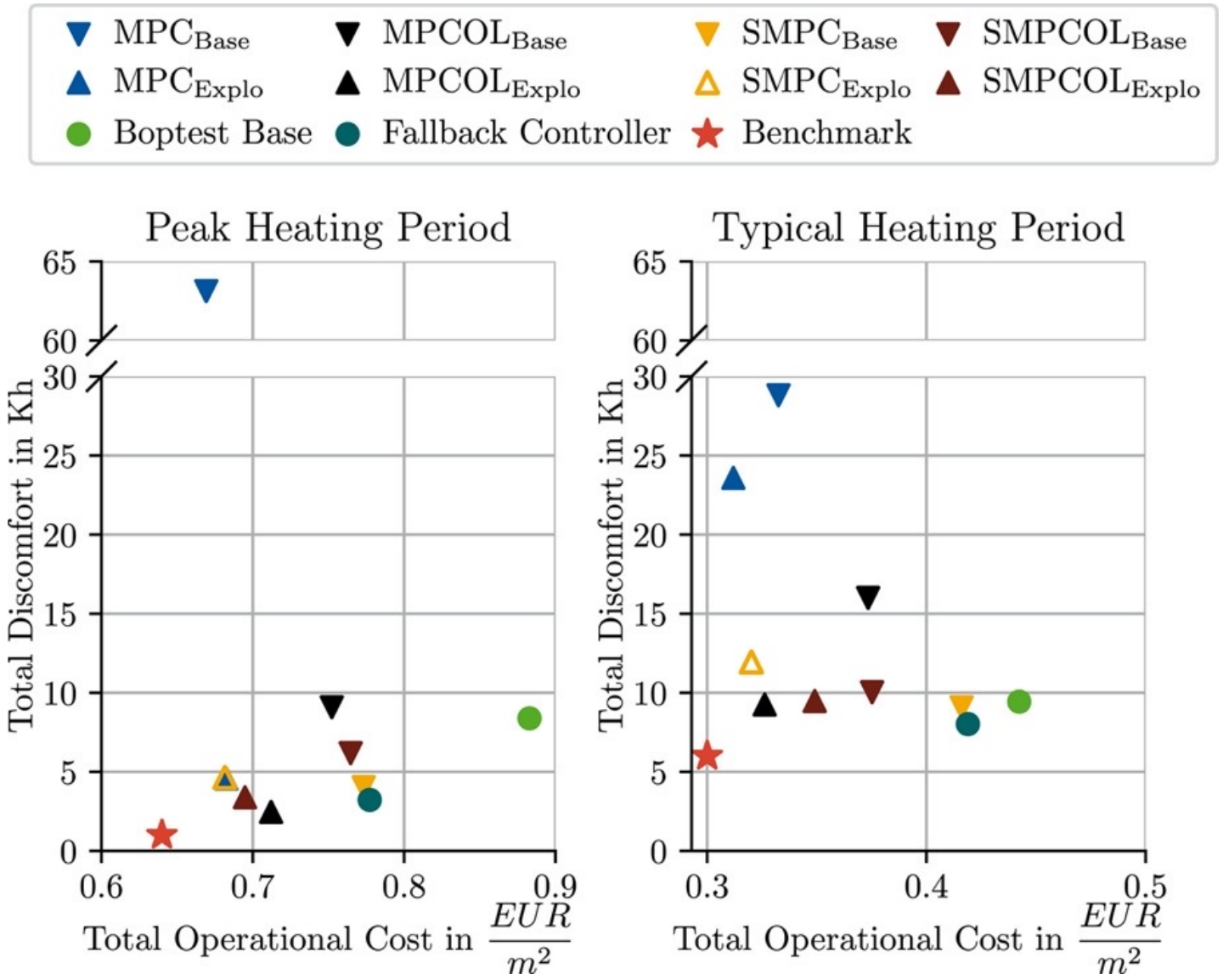
Implemented, but not yet available

Example Usage

Control Researchers

- Stoffel et. al. (2024). "Safe operation of online learning data driven model predictive control of building energy systems." *Energy and AI* https://doi.org/10.1016/j.egyai.2023.100296)

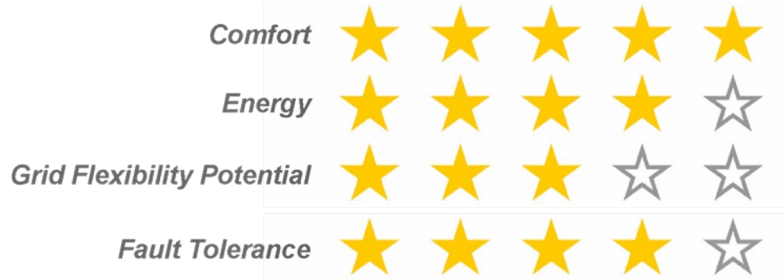
  "*The benchmark controller is a physics-based MPC from* ***Arroyo et al. 2022*** *for comparison.*"



Example Usage

Commercial Evaluation Services

ARUP

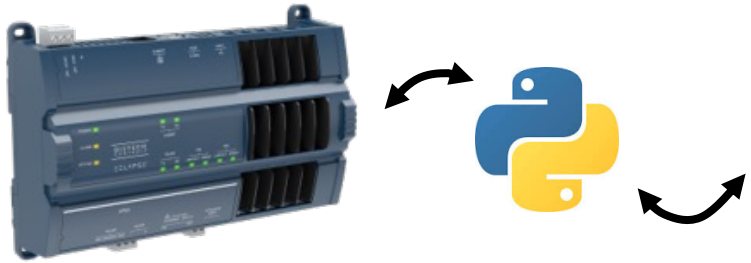


- Developing new business service to provide building owners comparative performance evaluations for control vendors offering predictive, data-driven, and grid-interactive controls.
- Developing control vendor evaluation workflows incorporating multiple elements, including screening questionnaires and BOPTEST trials.
- Developing Modelica and BOPTEST development skills in-house for client-specific test cases and BOPTEST deployment.
- Trialing service with two building portfolio owners in Australia.
- Proposed contract with LBNL (pending execution) to fund knowledge exchange and address issues identified during control vendor testing.

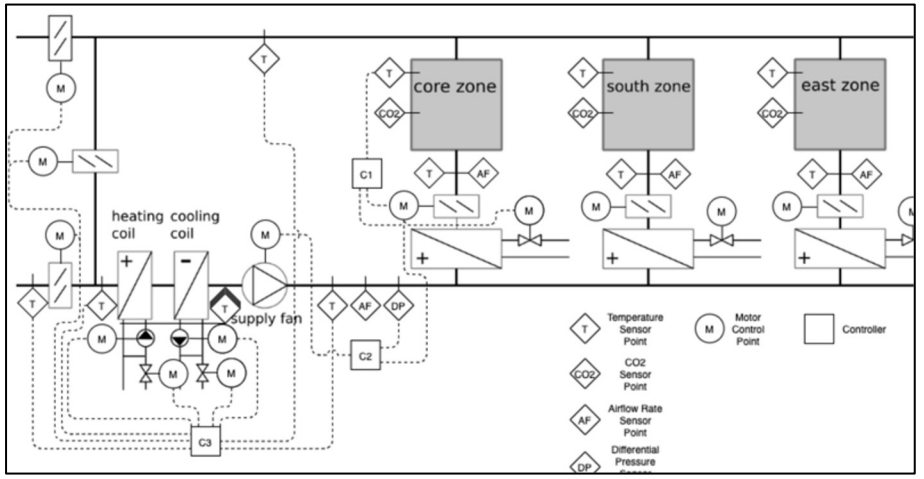
Example Usage

Control Product Development

DISTECH CONTROLS™



Points from BOPTEST are read and written to Distech ECLYPSE Controller



BOPTEST's Multizone Office Simple Air Test Case

- Testing Sequences of Operations to correct issues before deployment to customers
- Testing FDD Algorithms
- Training Customers on simulated data (e.g. system integrators and end users)
  - Ex. How to tune a PID loop, Building dashboards and trends with real data
- Testing RL algorithm performance and generating data for training
- Demonstrations for technical sales as well as sharing ideas internally

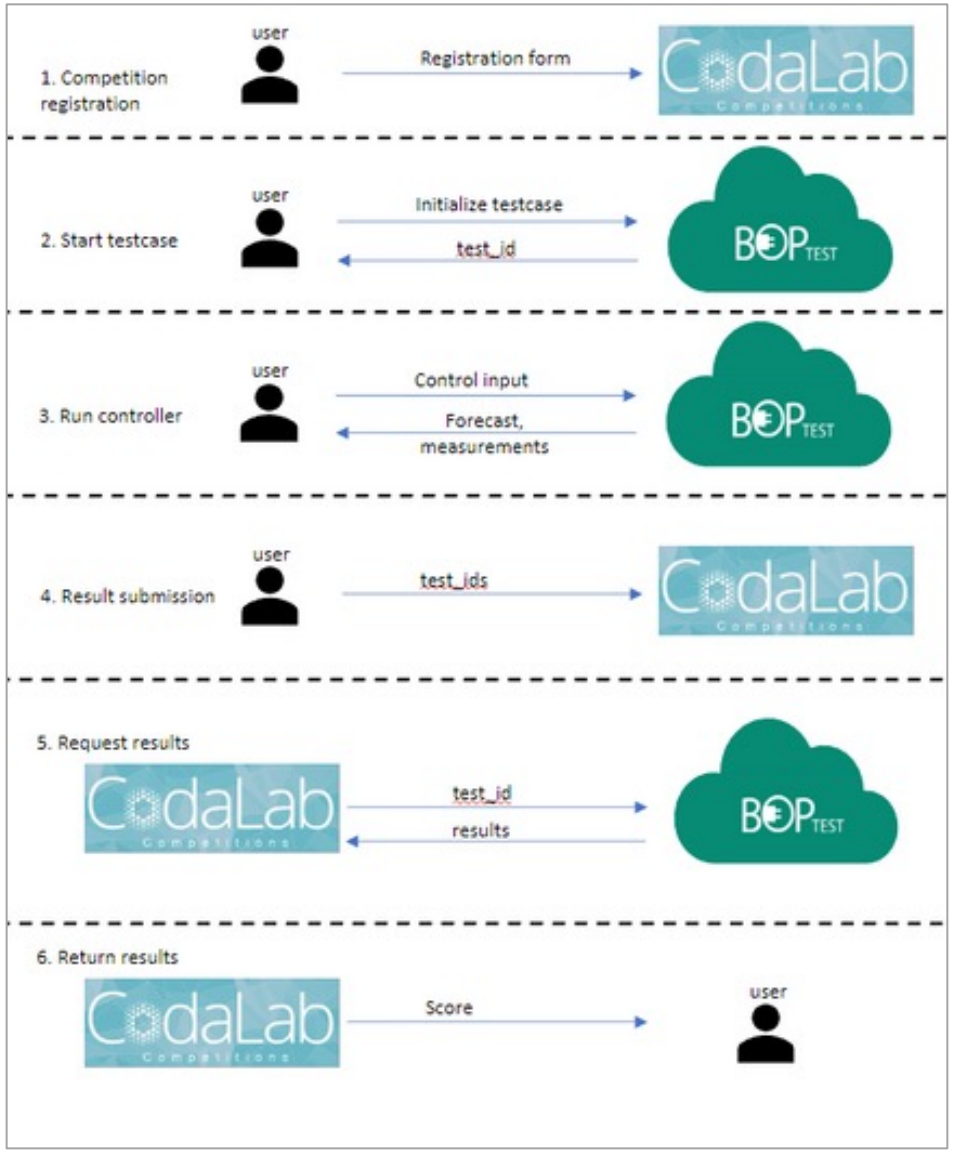
Example Usage

Smart Building Control Competition

ADRENALIN

https://adrenalin.energy/BOPTEST-Challenge-Smart-building-HVAC-control

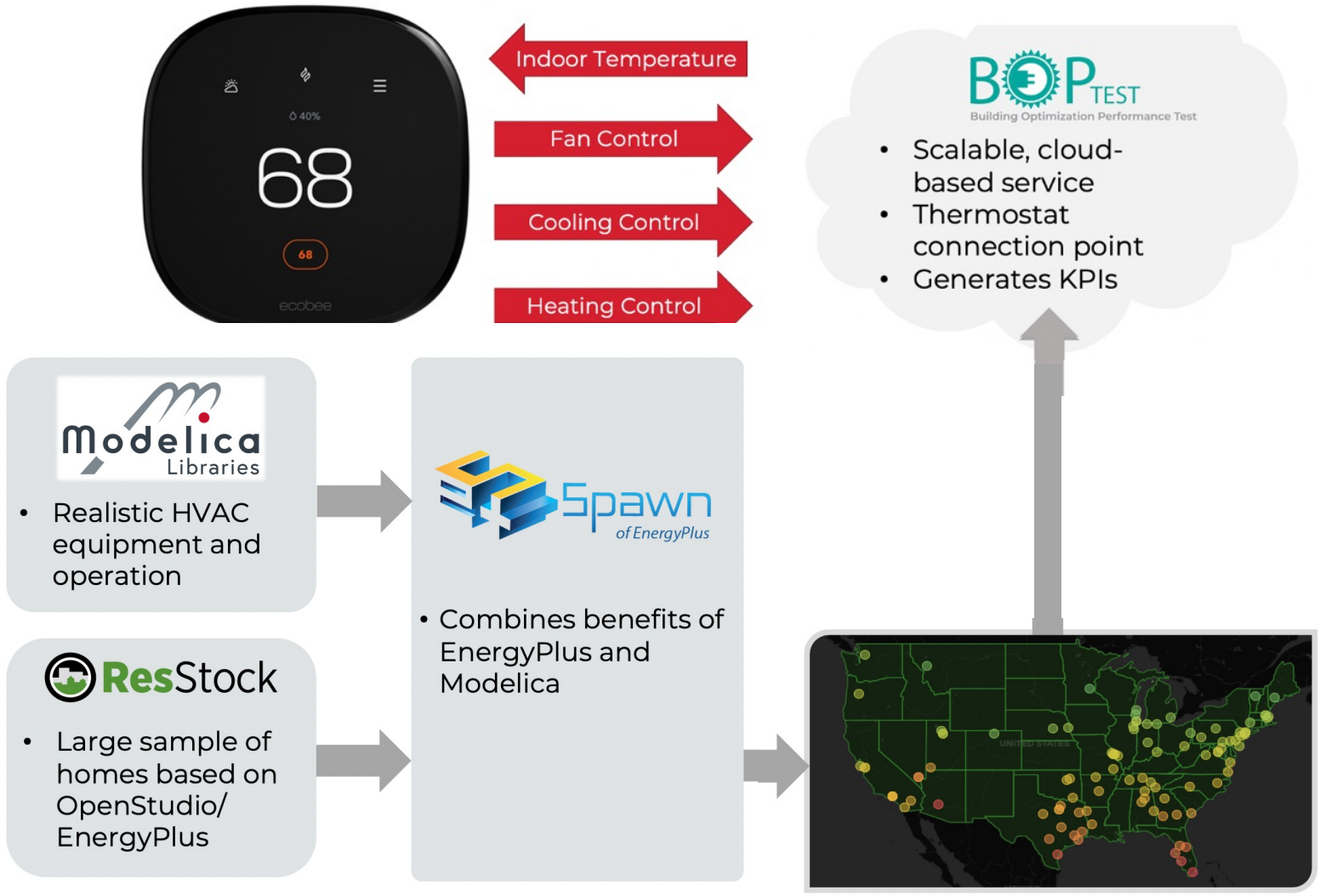
- Led by SINTEF
- Targets control algorithms for commercial buildings that reduces energy use and enable flexibility
- Best-performing solutions awarded prize money and chance to be implemented in real-life conditions
- Resulted in key lessons-learned for scaling usage of BOPTEST and using BOPTEST for competitive benchmarking



Example Usage

Large-Scale Thermostat Evaluation

- A framework has been assembled to evaluate thermostat algorithms in a range of scenarios.
- The tool is being used to help inform the EPA smart thermostat rating methodology.



Benne et al. (2024). “Simulation Driven Rating of Smart Thermostats.” In *Proc. of IBPSA USA SimBuild*. https://publications.ibpsa.org/conference/paper/?id=simbuild2024_2209

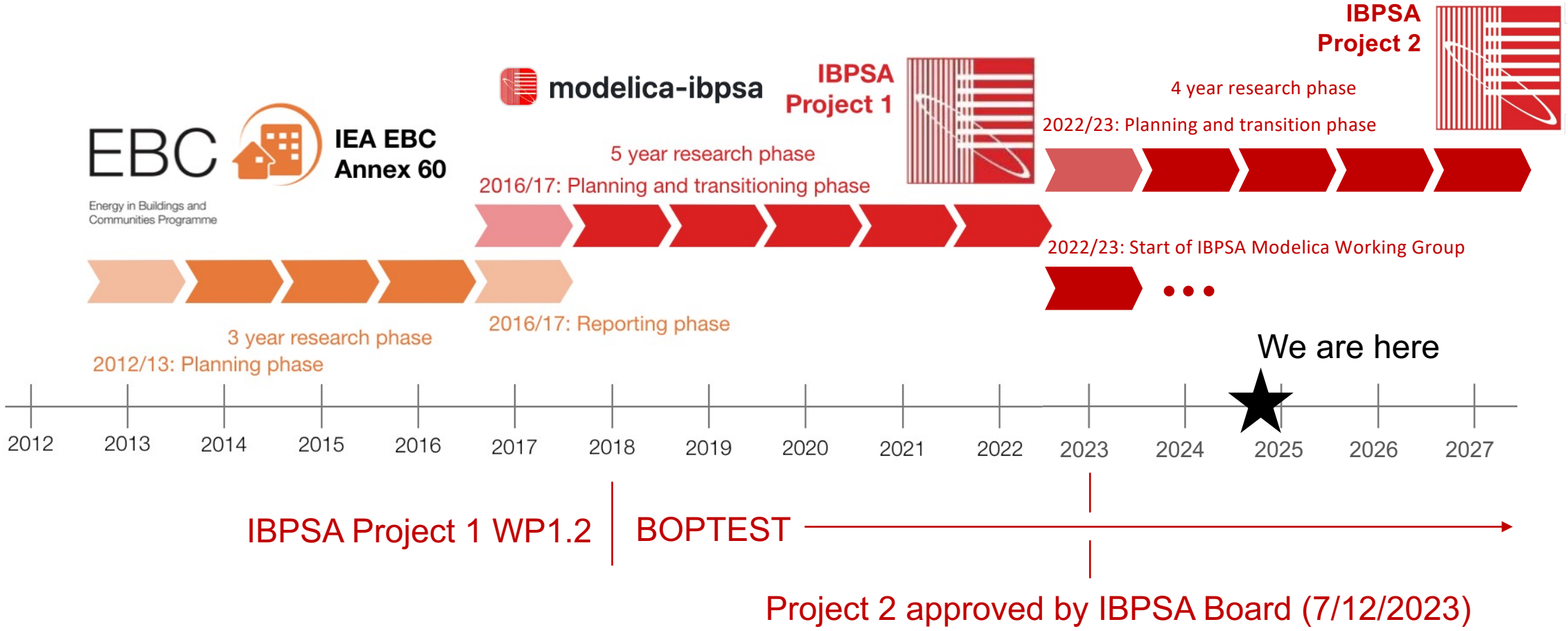
Project 2 Objectives

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 History

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



Project 2 Structure

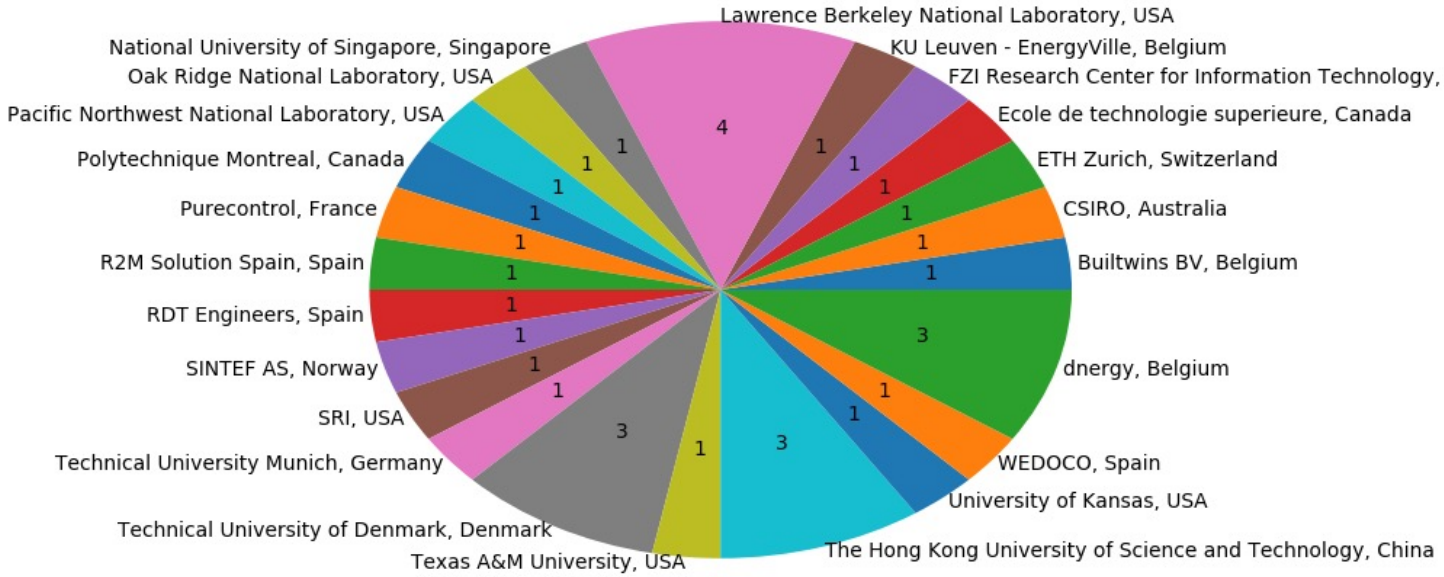
Co-Operating Agents: David Blum, LBNL and Lieve Helsen, KU Leuven - EnergyVille

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. E.g. workshops, tutorials, website, usage tracking.
2. **Task 2: Methods and Infrastructure**
   Lead: David Blum, LBNL, USA
   Development and maintenance of core software and closely related extensions. E.g. architecture, API, simulation and data management, KPI calculation, forecast delivery, online dashboard, web-service, and interfaces.
3. **Task 3: Test Cases**
   Lead: Ettore Zanetti, LBNL, USA
   Development and maintenance of test cases, including existing and new. Continue to utilize the Modelica language and Functional Mockup Interface (FMI) standards, and related tools.
4. **Task 4: Controller Testing**
   Leads: Esther Borkowski, ETH Zurich, Switzerland & Zhe Wang, HKUST, Hong Kong
   Testing, benchmarking, and comparison of control strategies by participants and BOPTEST users. Facilitate exchange of experiences and publication of results.

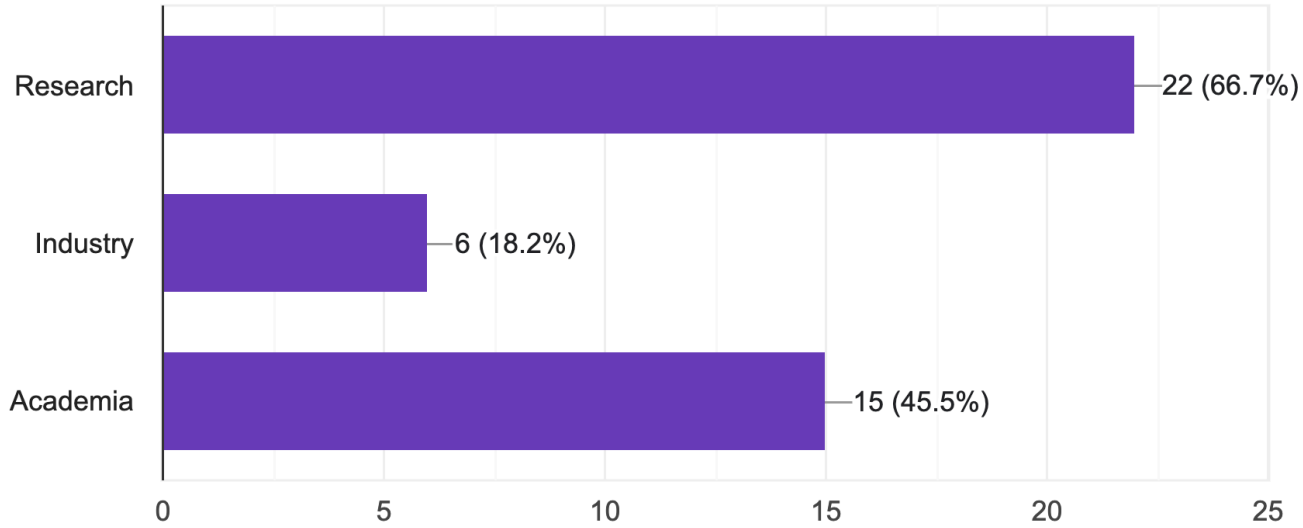
Project 2 Participation

As of October 25, 2024:
(registered using google form)

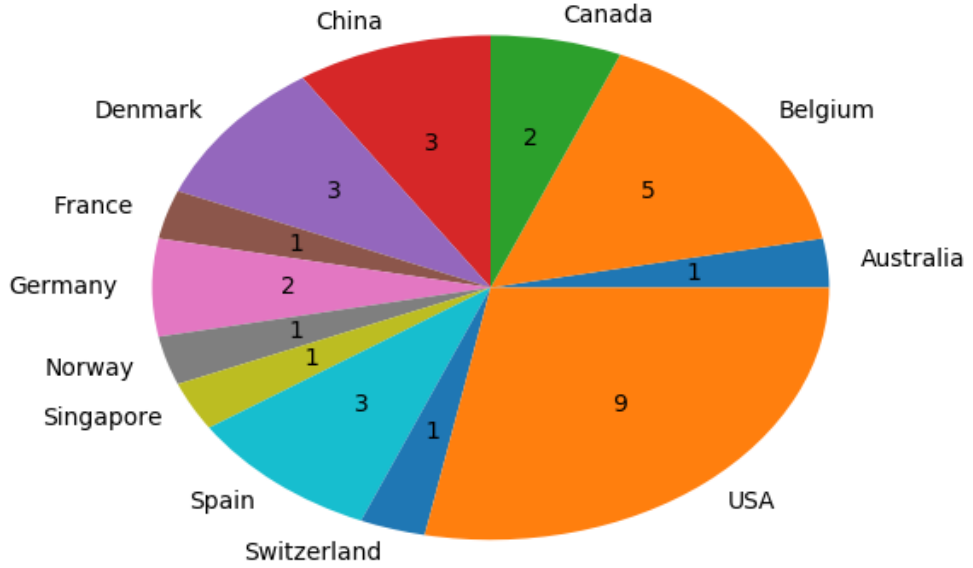
- 32 Registrants
- 23 Organizations
- 12 Countries



Breakdown by Organization



Breakdown by Organization Type



Breakdown by Country

Project 2 Participation

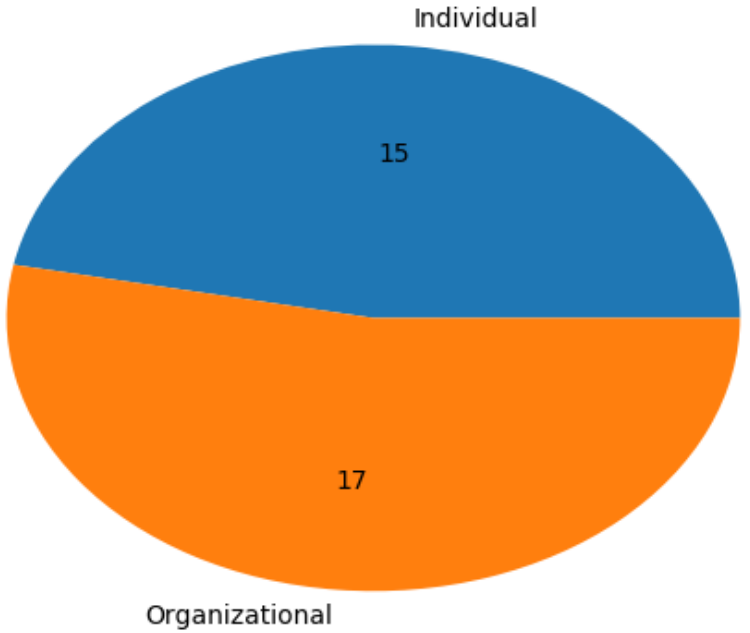
As of October 25, 2024:
(registered using google form)

- 32 Registrants
- 23 Organizations
- 12 Countries

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.

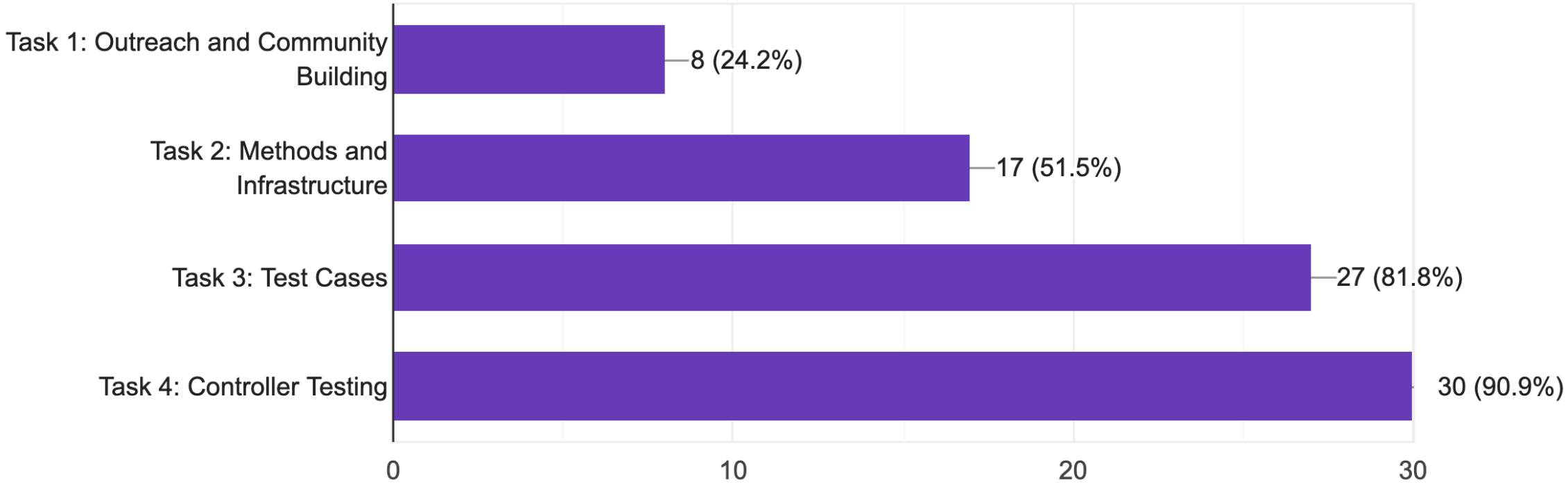
Sponsor: Participants or organizations that fund the Project with cash contribution at US-$ 5,000 per year. Go to items such as expenses for in-person expert meetings (i.e. rooms, food, A/V, and student travel scholarship) and CI testing.



Project 2 Participation

As of October 25, 2024:
(registered using google form)

- 32 Registrants
- 23 Organizations
- 12 Countries



Philosophical Aims

Commercial-Grade Open-Source Software

- Collaboration and commercialization-friendly licensing (BSD)
- Continuous-integration testing, maintenance, and support
- Structured development workflows using Git and GitHub
- Efficient, readable code

Peer-Based Development

- Code reviewed by at least one other person (maybe except small patches)
- Core methodology decisions validated by others
- Significant new features and test cases supported by sound R&D and publicly-available peer-reviewed publications (use acknowledgement text)

Collaboration Approach

- Transparency in project outputs (meeting minutes, slides, GitHub, etc.)
- Open to people, their ideas, and their experience
- Respect for each other