IBPSA Project 2: BOPTEST
Introduction and Project Status

Expert Meeting
Aachen, Germany

October 12, 2023

Co-Operating Agents:

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IBPSA Project 2: BOPTEST

Introduction and Project Status

Thank you to Fabian Wüllhorst and Professor Dirk Müller

IBPSA Project 2: BOPTEST
Introduction and Project Status

- Problem and BOPTEST Concept
- Development History
- Technical Approach Summary
- Status and Usage
- Project 2 Objectives, Tasks, and Registration Stats
- Publication Acknowledgement

Problem

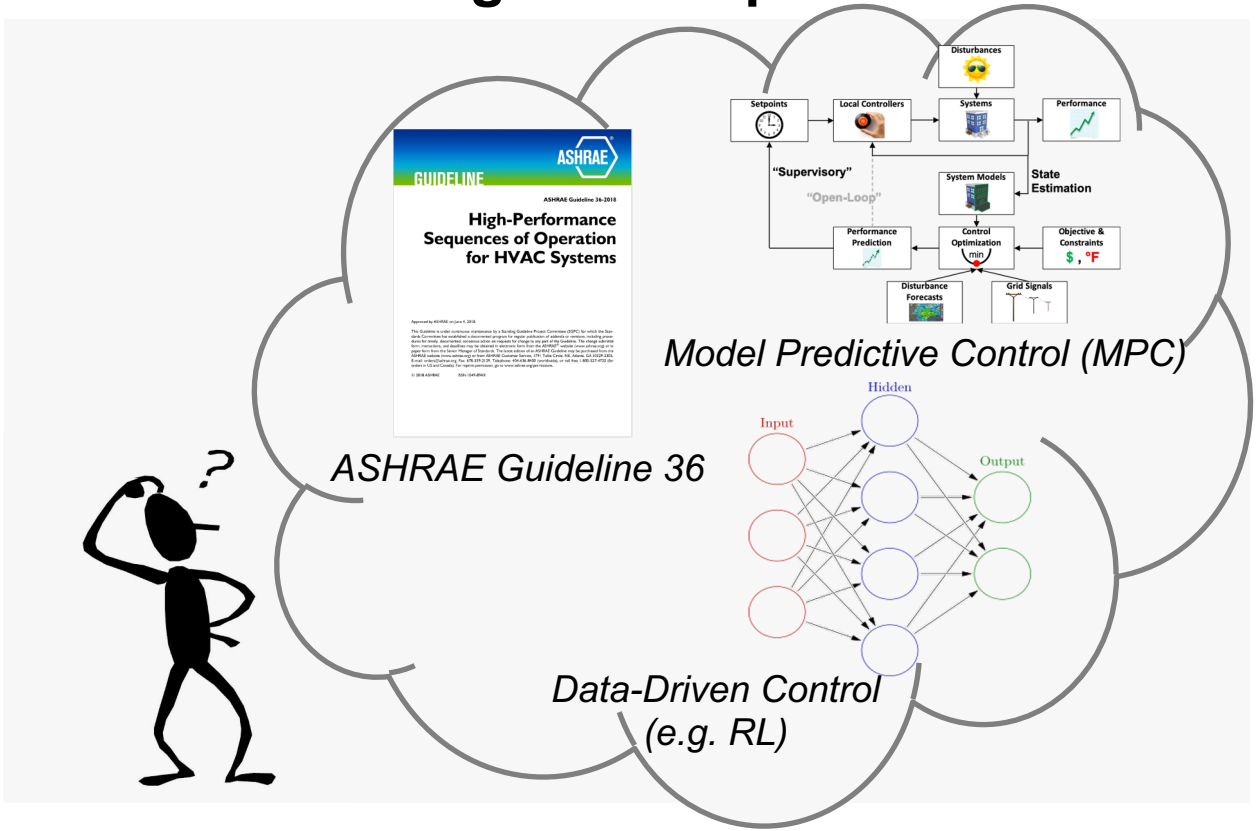
Many new and advanced control strategies hold promise …

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

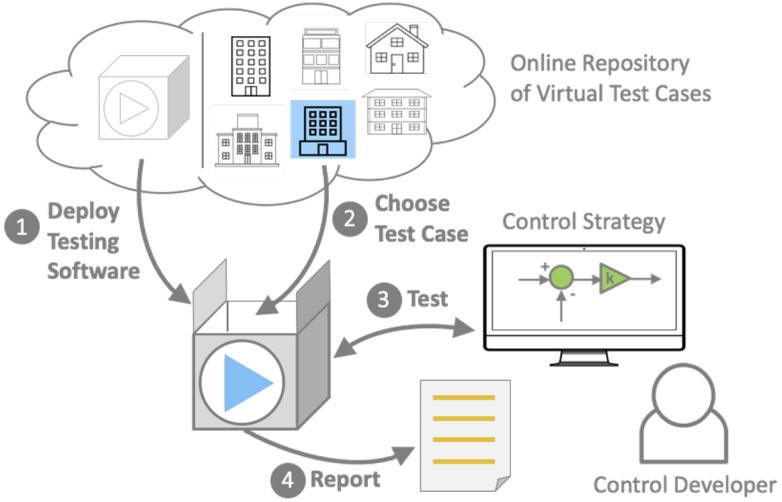


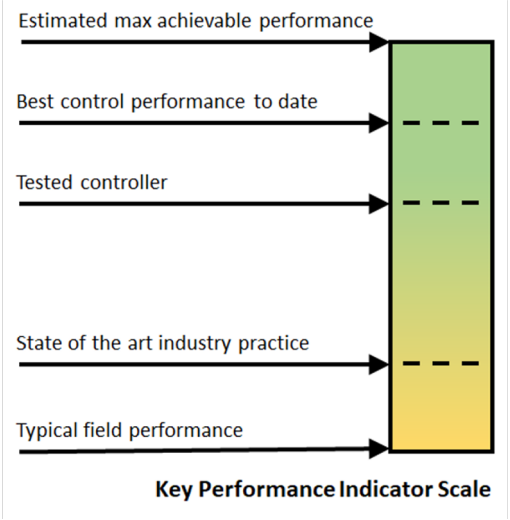
Concept

Building Optimization Testing Framework (BOPTEST)

A Simulation-Based Controls Testing and Benchmarking Environment

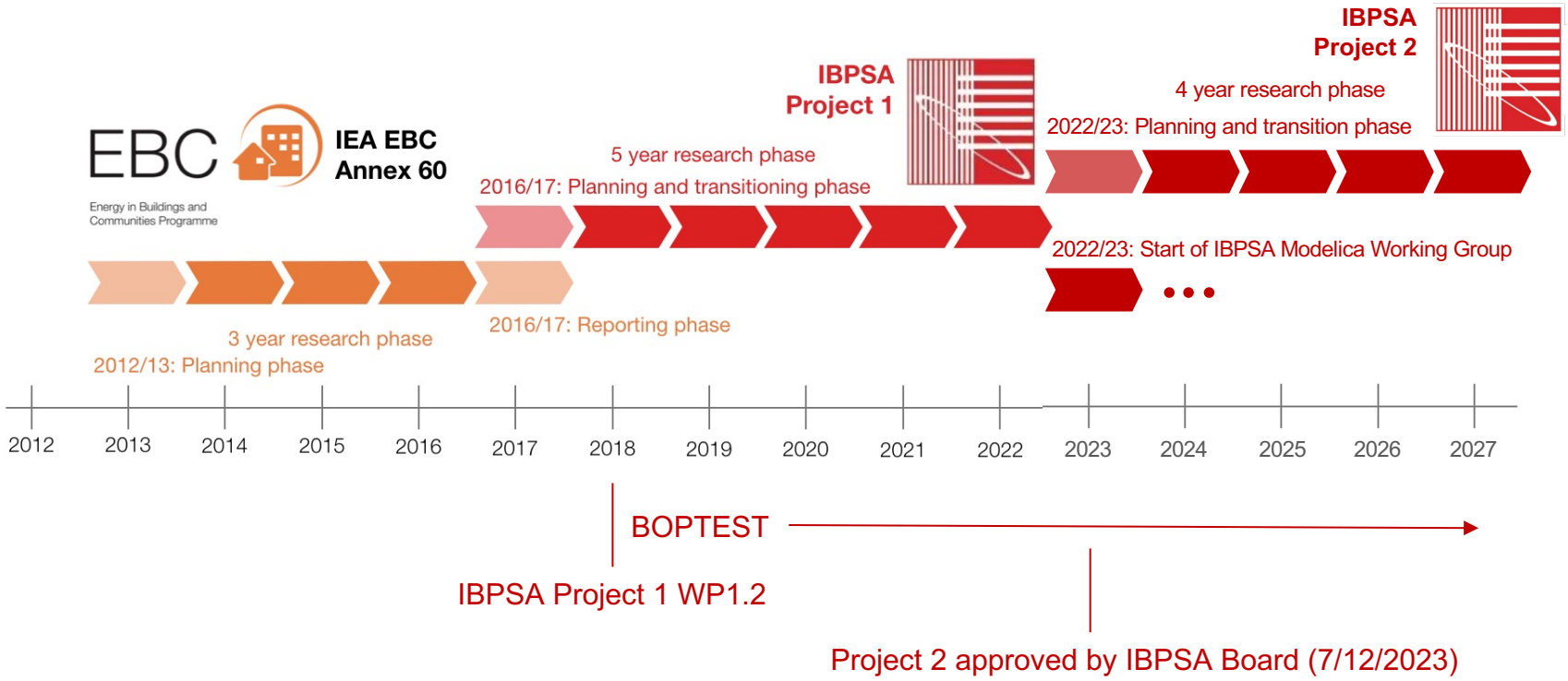
- Deployable software runtime environment: rapidly, repeatably, and at scale
- Control-interactive high-fidelity emulator models with defined boundary conditions
- Standardized key performance indicators (KPI) that are auto-calculated





History

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



Historical Community Development:

Institution	Team
Arup, Australia, USA, UK	Haico Schepers, Justin Prince, Robert Knight, Raffe Brennan
Builtwins, Belgium	Filip Jorissen
DeltaQ, 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, Javier Arroyo
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, Fabian Wullhorst
SINTEF, Norway	Harald Walnum
Southern Denmark University, Denmark	Krzysztof Arendt, Christian Veje, Tao Yang
Technical University of Denmark, Denmark	Peder Bacher, Konstantin Filonenko

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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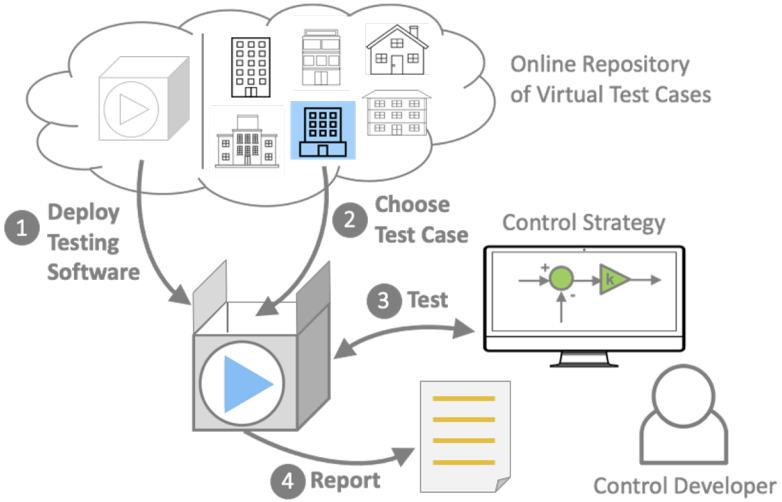
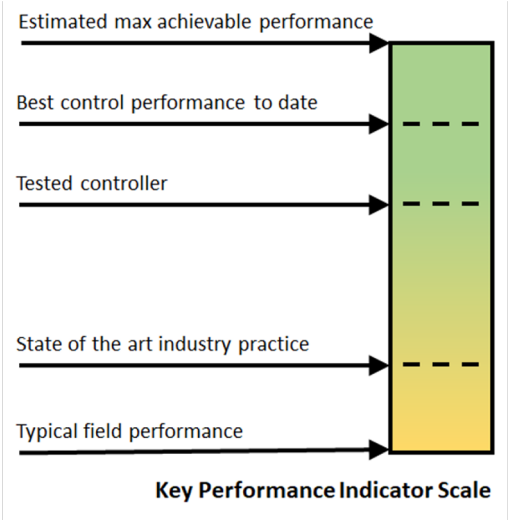
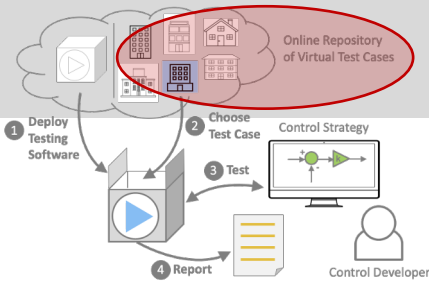


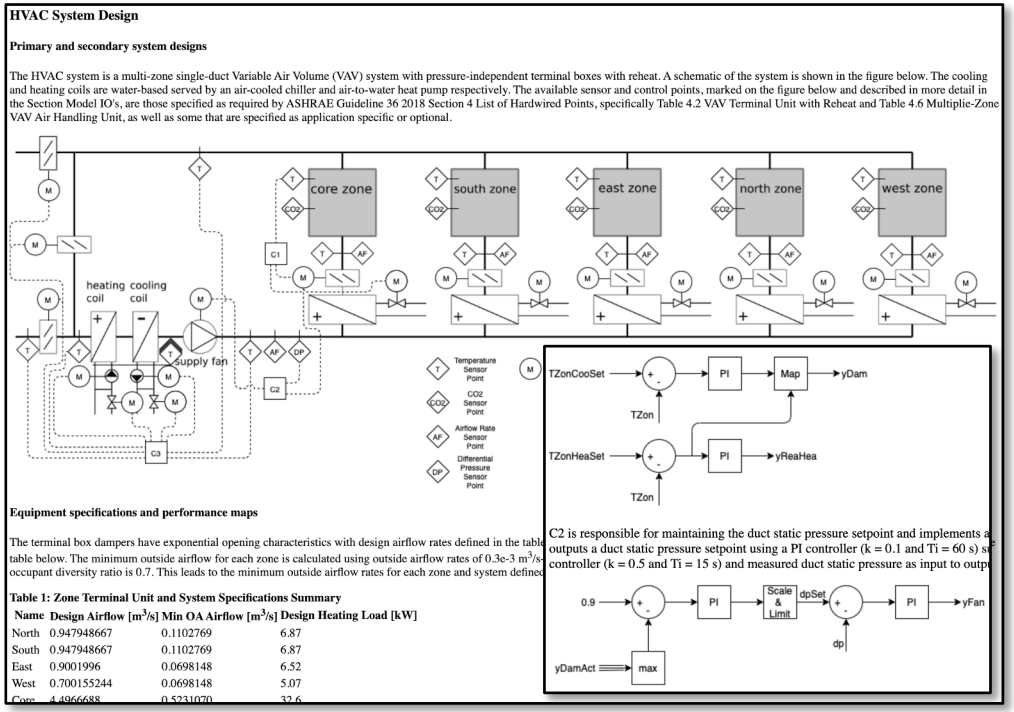


Approach



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

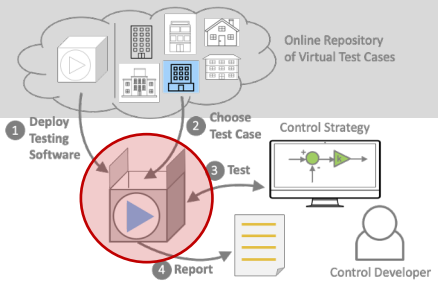
The terminal box dampers have exponential opening characteristics with design airflow rates defined in the table
table below. The minimum outside airflow for each zone is calculated using outside airflow rates of 0.3e-3 m^3/s-
occupant diversity ratio is 0.7. This leads to the minimum outside airflow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

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

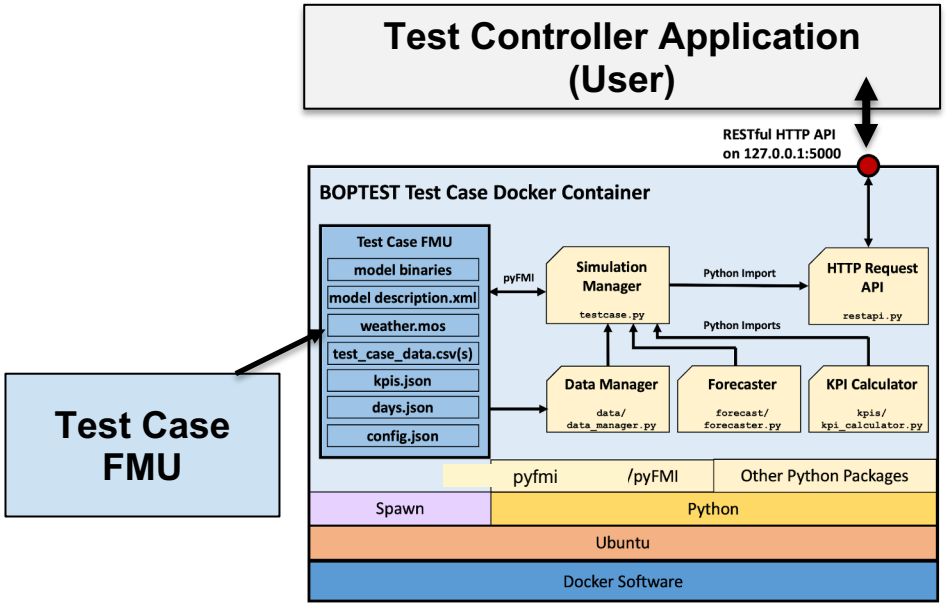


Run-Time Environment

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

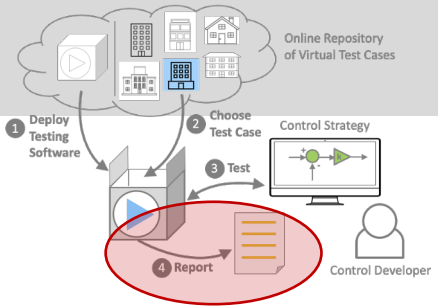
API Endpoint	Description
GET *measurements*	Receive available measurement points
GET *inputs*	Receive available input points
PUT *scenario*	Set test scenario (time period, ele. price)
PUT *initialize*	Initialize simulation
PUT *step*	Set control step
GET *forecast*	Receive forecasts
POST *advance*	Advance 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



Run-time environment architecture (for local deployment)

Approach



Evaluation Design

- Set of KPIs calculated by framework
- Predefined test scenarios
  (e.g. time period and electricity prices)
- Developing 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

Framework Status

- Home Page: https://boptest.net/
- BOPTEST v0.5.0 (last week) for core framework software and test cases: https://ibpsa.github.io/project1-boptest/
  - Release highlights:
    - Update Python 3.10, pyfmi 2.11, and CS FMUs
    - Added BACnet interface
  - v0.4.0 Downloads (Mar – Oct, 2023): 85
  - GitHub: 75 Stars, 54 Forks
- BOPTEST-Service v0.3.0 (last week) with support for BOPTEST v0.5.0: https://github.com/NREL/boptest-service
  - public web-service API https://api.boptest.net
  - supporting BOPTEST v0.4.0 (v0.5.0 any day)
- Gym environment interface with support for v0.4.0: https://github.com/ibpsa/project1-boptest-gym
- BOPTEST Online Results Dashboard: https://dashboard.boptest.net/

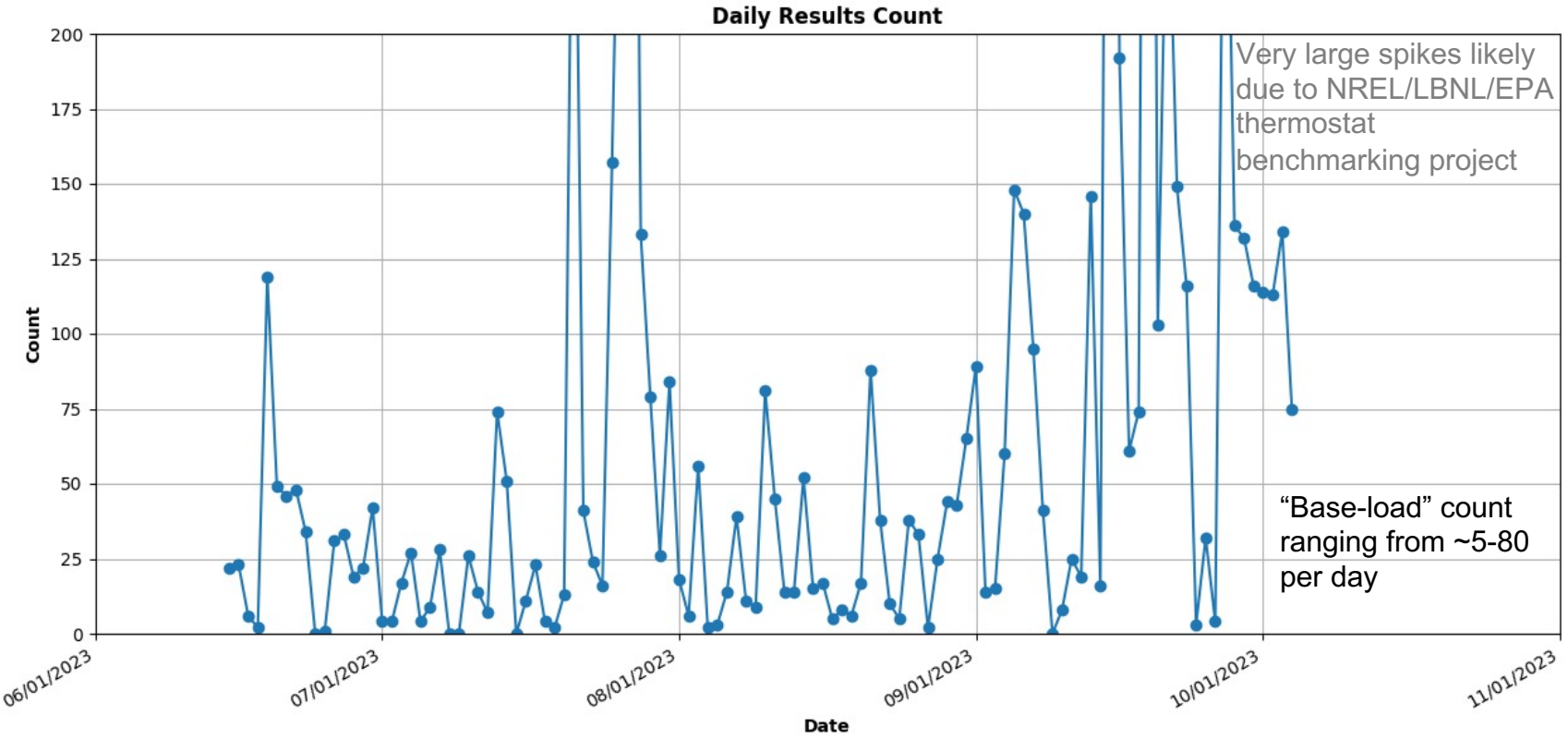
Hydronic	Air
Single zone + Radiator *"bestest_hydronic"*	Single zone + FCU "*bestest_air*"
Single zone + Floor heat and heat pump *"bestest_hydronic_heat_pump"*	Single zone + RTU with DX, gas furnace
2 zone + Floor heat and heat pump *"twozone_apartment_hydronic"*	2 zone + FCUs + AHUs with gas boiler, 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

Framework Usage

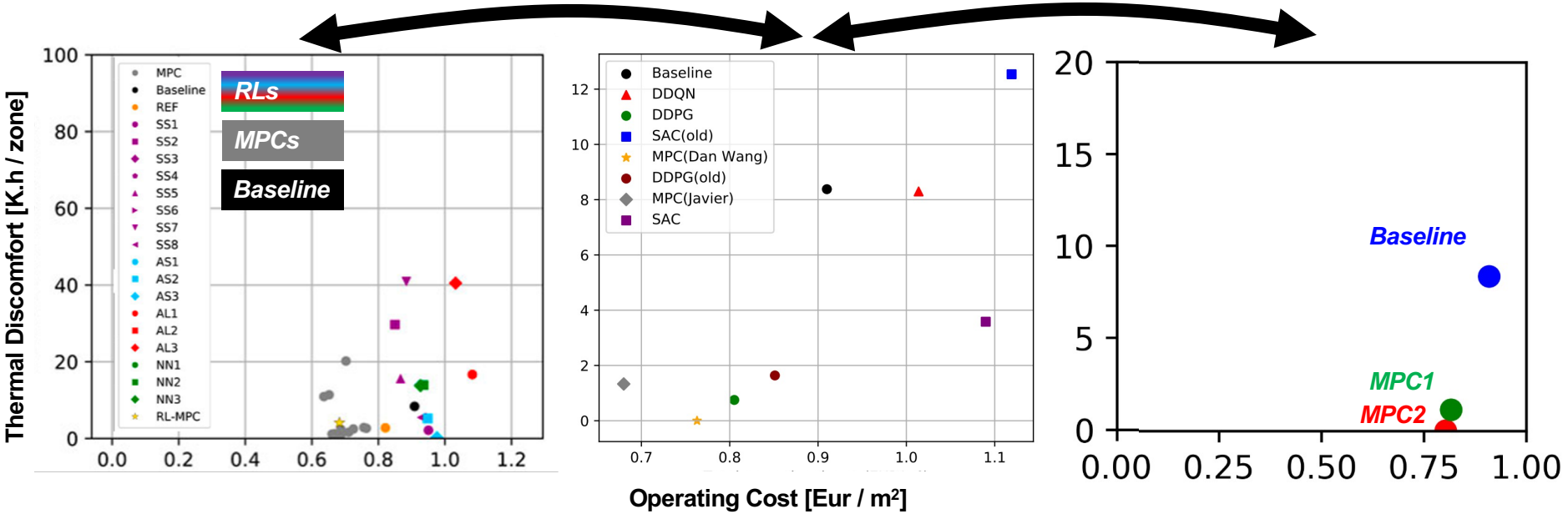
Public Web-Service Usage (number of results created per day)



Framework Usage

Research Example

Test Case: “bestest_hydronic_heat_pump”
Scenario: Peak Heat Day, Highly Dynamic Electricity Price



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

MPC and RL benchmarking, presented in Annex 81 Subtask B3 progress meeting on 6/23/22. Final study is Wang and Zheng et al. 2023 https://doi.org/10.1016/j.applthermaleng.2023.120430.

MPC benchmarking, presented in Annex 81 Subtask B3 plenary meeting on 10/13/22, from H. T. Walnum.

Framework Usage

Industry Examples

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

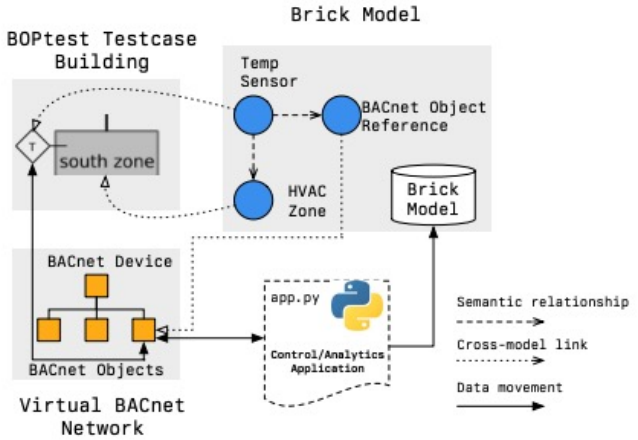
ARUP (Australia, USA, UK)
Exploring usage to provide building owners comparative performance evaluations for advanced controls

EPA EnergyStar (USA)
Exploring usage for improving Smart Thermostat rating system

ADRENALINE (Led by Norway)
Smart Building HVAC Control Challenge open competition

Johnson Controls (USA, 2022-2023)
Improve deployment process of new control products through Semantic models and BACnet

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



Prototyped control application deployment with BACnet, Brick, and BOPTEST (Fierro et al. 2022 https://dl.acm.org/doi/pdf/10.1145/3563357.3564060)

Project 2 Objectives

- 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, KU Leuven, Belgium

   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.

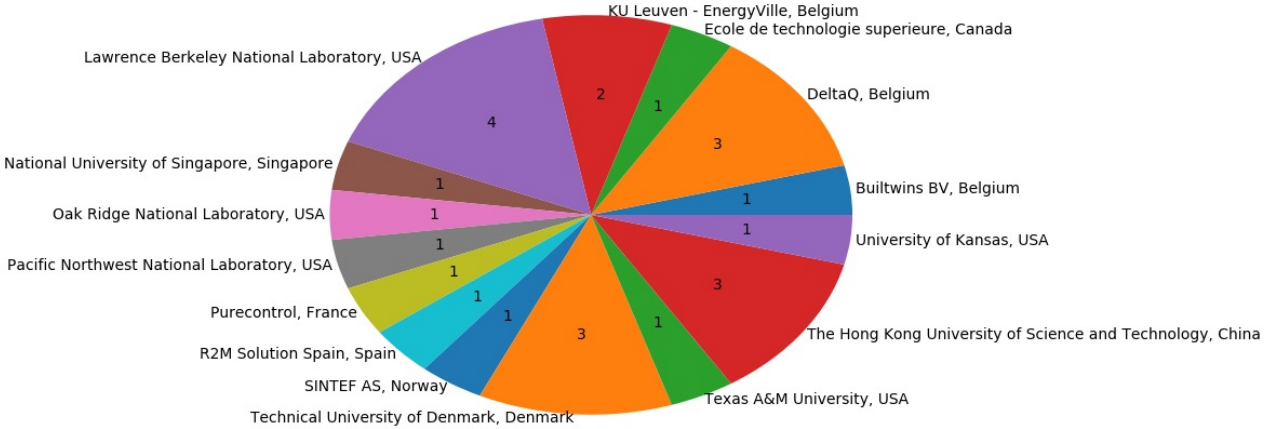
4. **Task 4: Controller Testing**
   Co-leads: Esther Borkowski, ETH Zurich, Switzerland & Zhe Wang, HKUST, Hong Kong

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

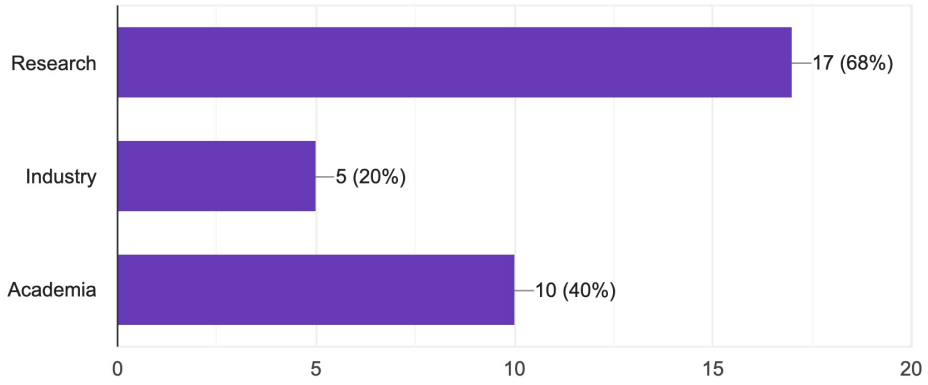
Project 2 Participation

As of October 6, 2023:
(registered using google form)

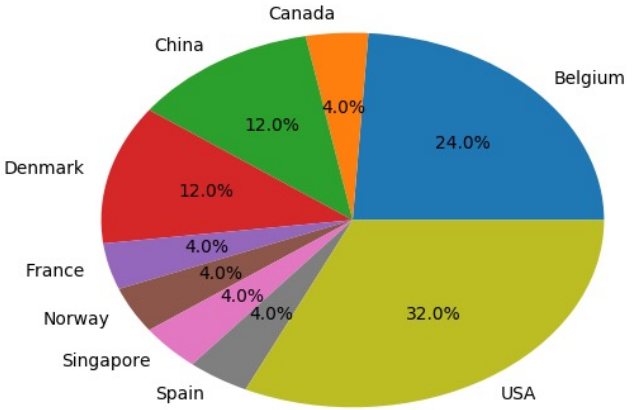
- 25 Registrants
- 16 Organizations
- 9 Countries



Breakdown by Organization



Breakdown by Organization Type



Breakdown by Country

Project 2 Participation

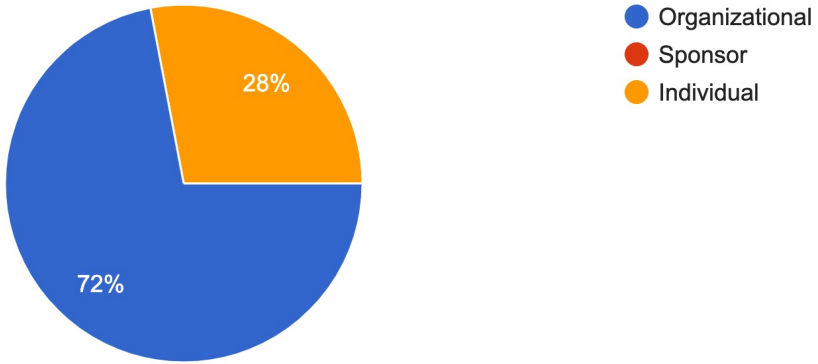
As of October 6, 2023:
(registered using google form)

- 25 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 Contributions

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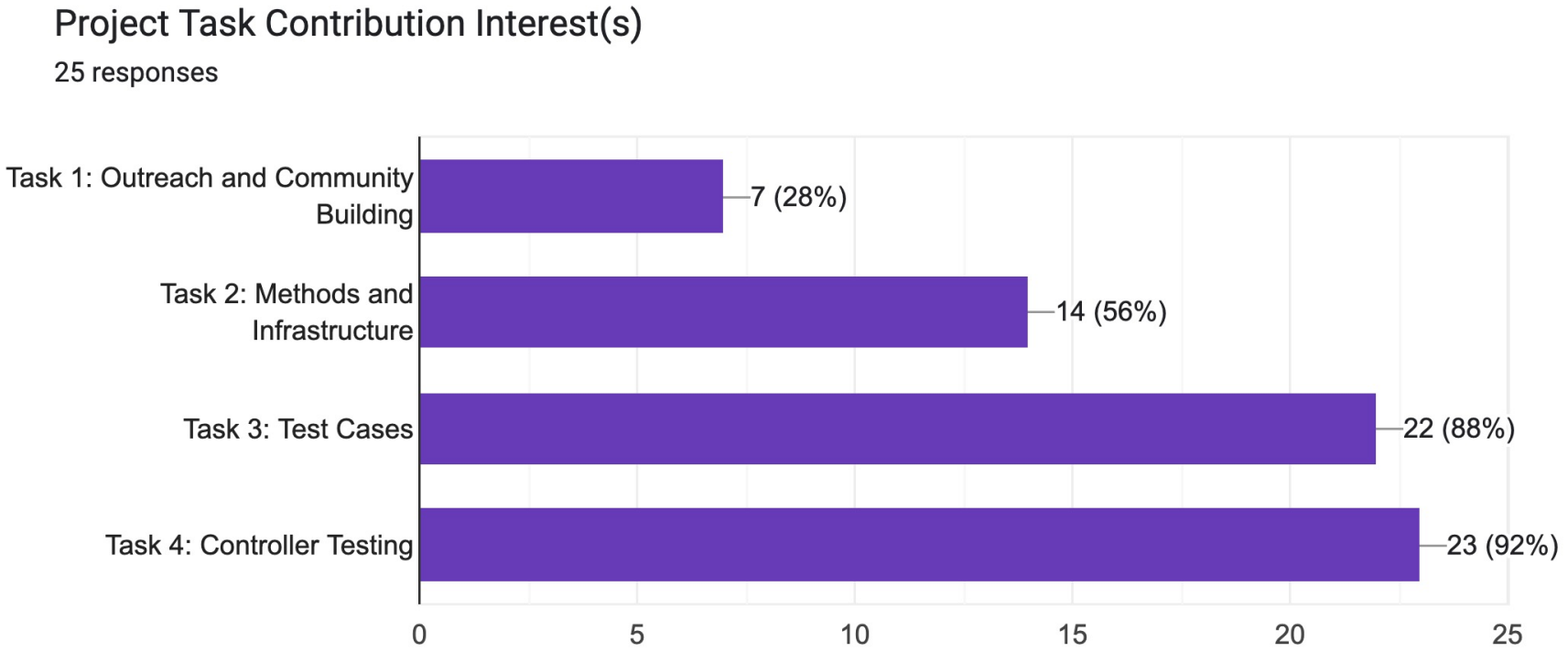

Project 2 Publication Acknowledgement

This work emerged from the IBPSA Project 2, an international project conducted under the umbrella of the International Building Performance Simulation Association (IBPSA) to develop and demonstrate the Building Optimization Testing Framework (BOPTEST) for the testing, evaluating, and benchmarking of building and community energy system controls.