IBPSA Project - Building Optimization Testing Framework (BOPTEST)

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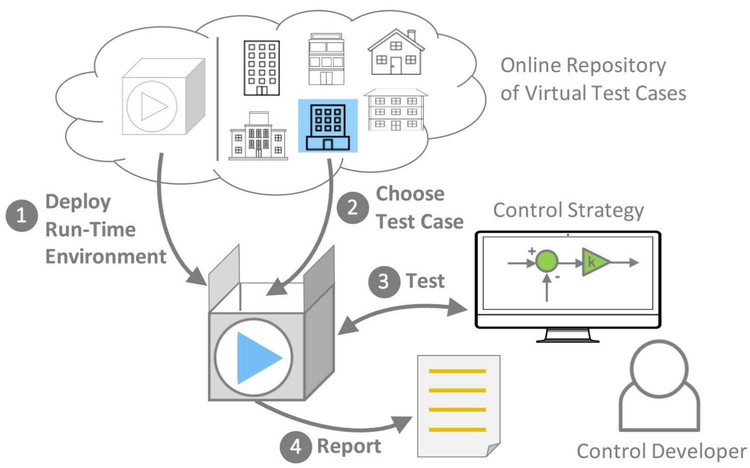
Abstract

Needs for advanced and improved control strategies (CS) in building and district energy systems are growing due to requirements for reducing energy use, emissions, and operating costs, providing grid flexibility, and ensuring performance of novel hybrid and collective system architectures. Examples of such CS are advanced rule-based control, Model Predictive Control (MPC), and Reinforcement Learning (RL). However, while these and other CS show promise, three challenges slow their widespread adoption: 1) The performance of each CS is typically demonstrated on individualized case studies and quantified using different metrics, making it difficult to benchmark and compare their performance, identify the most promising approaches, and identify needed development. 2) Demonstrations in real buildings and district energy systems pose large operational risks and difficult environments for controlled experiments. 3) Development of realistic simulation models for CS testing and evaluation require significant building science and modeling expertise not necessarily held by experts from fields which could contribute to new CS development, such as process control, optimization, and data science. The building simulation (BS) community can address these challenges by providing suites of publicly available, high-fidelity simulation models, called emulators, to be used for rapid-prototyping and benchmarking CS.

This IBPSA Project will continue development of the Building Optimization Testing Framework (BOPTEST), work started under IBPSA Project 1 WP1.2. BOPTEST contains three main components: 1) public, rapidly and repeatably shareable high-fidelity building emulators and boundary conditions (so-called "test cases"), 2) run-time environment (RTE) deployed locally or as a web-service which exposes a highly accessible HTTP RESTful API for test subject controllers to interact with the test cases as if they were real buildings, and 3) key performance indicators (KPI) calculated within the RTE based on simulation data and made available to users and for posting to an online results dashboard for viewing, comparing, and sharing publicly. Project tasks include community engagement and outreach, maintenance of the software and development of new features, maintenance of existing test cases and development of new ones for new applications, and demonstrated use of BOPTEST for CS prototyping and benchmarking.



The Building Optimization Testing Framework (BOPTEST) concept.

Overview

Needs for advanced and improved control strategies (CS) in building and district energy systems are growing due to requirements for reducing energy use, greenhouse gas emissions, and operating costs, providing flexibility to the electrical grid, as well as ensuring performance of novel hybrid and collective system architectures. Examples of such CS are advanced rule-based control, Model Predictive Control (MPC) [Drg20], and Reinforcement Learning [Wan20]. However, while these and other CS show promise, three challenges slow their widespread adoption:

1. The performance of each CS is typically demonstrated on individualized case studies and quantified using different metrics, making it difficult to benchmark and compare their performance, identify the most promising approaches, and identify needed development.
2. Demonstrations in real buildings and district energy systems pose large operational risks and difficult environments for controlled experiments.
3. Development of realistic simulation models for CS testing and evaluation requires significant building science and modeling expertise not necessarily held by experts from fields which could contribute to new CS development, such as process control, optimization, and data science.

The building simulation (BS) community can address these challenges by providing suites of publicly available, high-fidelity simulation models, called emulators, to be used for benchmarking CS. Furthermore, providing a comprehensive framework to deploy, interact with, and generate key performance indicators (KPI) from these emulators would ensure their benchmarking capability and make them readily available to related control and data science fields outside of the BS community. There exists precedent for such an approach within the BS field with the development of the BESTEST [Jud95] and subsequent ASHRAE Standard 140 [ASH11] as well as the optimization fields (e.g. Decision Tree for Optimization Software [Mit22]) and data science (e.g. OpenAI Gym [Ope22]).

Work is underway on the envisioned framework and emulators, called the Building Optimization Testing Framework (BOPTEST). BOPTEST has been developed within the IBPSA Project 1 Work Package 1.2, with primary software development occurring at https://github.com/ibpsa/project1-boptest, which is open-source with IBPSA copyright, and emulator development (so-called "test cases") focusing on individual building systems. The framework is described in [Blu21] and has been used in [Arr20, Arr22, Bun21, Hua18, Wal20, Yan20, Zan22]. A home page is hosted at https://ibpsa.github.io/project1-boptest. Additional related development has created an OpenAI Gym interface (https://github.com/ibpsa/project1-boptest-gym), made BOPTEST available as a web-service (hosted at https://api.boptest.net with open-source web-service software at https://github.com/NREL/boptest-service), and created an online dashboard to share and sort results (hosted at https://dashboard.boptest.net with open-source dashboard software at https://github.com/NREL/boptest-dashboard).

This new IBPSA Project ("Project") will extend the work of IBPSA Project 1 WP1.2, further developing BOPTEST software infrastructure, emulators, and related extensions to meet the growing needs of CS development and evaluation for building and district energy systems worldwide. Software development will continue under the same open-source license to facilitate community development and to enable access to all, including third-party developers to build applications utilizing BOPTEST.

Project contact (operating agents)

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Project participants

This is an initial participant list (arranged by Family Name) and subject to change. It is based on a combination of personal communication of interest, attendance to recent coordination meetings, and joining of google group used for email announcements.

Given Name	Family Name	Institution	Country
Rossella	Alesci	Politecnico di Milano	Italy
Peder	Bacher	Technical University of Denmark	Denmark
Yeonjin	Bae	Oak Ridge National Laboratory	USA
Kyle	Benne	National Renewable Energy Laboratory	USA
David	Blum	Lawrence Berkeley National Laboratory	USA
Esther	Borkowski	ETH Zurich	Switzerland
Clara	Ceccolini	University of Freiburg, Bosch	Germany
Roel	De Coninck	DeltaQ	Belgium
Davide	Fop	Politecnico di Torino	Italy
Lieve	Helsen	KU Leuven	Belgium
Yan	Chen	Pacific Northwest National Laboratory	USA
Filip	Jorissen	Builtwins	Belgium
Justin	Prince	Arup	USA
Dimitrios	Rovas	University College London	England
Harald	Walnum	SINTEF	Norway
Zhe	Wang	The Hong Kong University of Science and Technology	Hong Kong
Laura	Zabala	R2M Solution	Spain
James	Zhan	National University of Singapore	Singapore

Structure

Task 1: Outreach and Community Building

This task will focus on activities that encourage, facilitate, and disseminate BOPTEST usage, adoption, and feedback to development. Specific objectives are as follows:

1. Survey and engage with the research and practitioner communities to inform software and test case development, such as suggesting useful software functionality and identifying the most interesting control problems or applications.
2. Collect known case studies making use of BOPTEST and testimonials from various stakeholders in the control design, delivery, ownership, and policy-making process who find value in BOPTEST.
3. Develop and deliver workshops and tutorials on the usage of BOPTEST, either stand-alone or in coordination with conferences sponsored by IBPSA or other relevant organizations.
4. Collect, track, and report usage statistics, such as papers citing BOPTEST, number of tests run using the web-service, number of results reported to online results dashboard, and software release downloads.

A project website (currently at https://ibpsa.github.io/project1-boptest/) will provide information for the various components of BOPTEST as well as listing and making available outreach material such as publications, workshops, and tutorials.

Task 2: Methods and Infrastructure

This task will focus on development and maintenance of core framework software and closely related extensions in response to needs identified by Project participants and community feedback. Related components include test case and framework architecture specification, FMU simulation and data management, KPI calculation, forecast delivery, API, online results sharing dashboard, web-service, and interface extensions. While development will be informed by community engagement in Task 1, specific initial topics of interest include:

1. Maintenance and enhancement of existing infrastructure where needed, such as improving computation methods and maintaining compatibility with evolving dependent software.
2. Migrate to OpenModelica and Spawn as primary open-source test case FMU compilers, update to Modelica Standard Library v4.0.0, utilize recent releases of dependent modeling libraries extending from the Modelica IBPSA Library, and update to FMU v3.0. This will be in coordination with Task 3.
3. Storing and providing semantic model information such as that specified in ASHRAE Standard 223p, Brick, and Haystack.
4. Implementation of new KPI calculations as needed.
5. Characterization and implementation of uncertainty in forecasts of disturbances, such as weather, occupancy, and internal load.
6. Characterization and implementation of uncertainty in measurements, such as sensor noise and bias. This will be in coordination with Task 3 regarding specific test case needs.
7. Implementation of test scenarios that introduce system faults, such as stuck actuators, dirty or clogged heat exchangers, and missing data. This will be in coordination with Task 3 regarding specific test case needs.
8. Implementation of new API functionality as needed.

9. Enhancement of the online results sharing dashboard, including characterization of controllers.
10. Enhancement and development of relevant interfaces, such as for OpenAI Gym and BACnet communication.

Task 3: Test Cases

This task will focus on development and maintenance of benchmark emulators, so-called "test cases." Emulator development will continue to utilize the Modelica language and Functional Mockup Interface (FMI) standard, particularly open-source libraries that extend from the Modelica IBPSA Library developed through IBPSA Project 1 WP1.1 and continuation Working Group.

One focus of this task will be maintaining test cases developed as part of IBPSA Project 1 WP1.2, in coordination with Task 2, including migration to OpenModelica and Spawn as primary open-source test case FMU compilers, updating to Modelica Standard Library v4.0.0, utilizing recent releases of dependent Modelica libraries extending from the Modelica IBPSA Library, and updating to FMU v3.0 when possible.

Another focus of this task will be creating new test cases depending on participant and community interest, as well as consideration for relevant standards and guidelines. Example new applications of interest include:

1. District heating and cooling systems
2. National building stock representation
3. Active thermal energy storage and other distributed energy resource management
4. Electric grid integration
5. Integrated multi-energy district systems

The outcome will be a core set of test cases (so-called "IBPSA Test Cases") developed by Project participants that will exist within a repository maintained and licensed by IBPSA through Project participants, which will be the same as or extend that already developed in IBPSA Project 1 WP1.2 at https://github.com/ibpsa/project1-boptest. Such emulators will be carefully chosen following an internal code defined by the Project participants during the initial months of the Project and will undergo a peer-review process developed under IBPSA Project 1 WP1.2, enhanced as needed in this Project, to maintain quality, multi-partner relevance, and usability assurances. On top of that, individuals and organizations may develop additional BOPTEST-compliant emulators of their interest and maintain and license them as they see fit in separate repositories owned by them (so-called "Non-IBPSA Test Cases"). Such developers may participate in the Project by offering or accessing lessons learned of emulator development and serving as reviewers in the peer review process for IBPSA Emulators. These separately-developed emulators may be added to the core set of emulators if considered appropriate and the established peer review process is completed.

Task 4: Controller Testing

This task will focus on testing and benchmarking CS developed by both participants in this Project, and also comparison with CS developers external to the Project, using the framework developed in Task 2 and test cases developed in Task 3. The outcome will be results (based on multiple KPIs) submitted to the online dashboard, as well as relevant publications and presentations in appropriate venues.

Timeline

All tasks will be performed in parallel. The project intends to start January 2023 and last until December 2027.

Deliverables and milestones

Deliverables

By project's end:
D1: Project website
D2: Open-source repository for core BOPTEST software infrastructure
D3: Open-source repository of test cases
D4: On-line dashboard showing tested and benchmarked CS on multiple IBPSA Test Cases

Milestones

Name	Description and Completion Criteria	Due Date
M1 Project website	Continuous maintenance of the project website. Contributes to D1.	Continuously maintained until December 2027
M2.1 - 2.5 Core software release	At least one new release of new version of core software from GitHub repository. Contributes to D2.	Each September, 2023-2027
M3.1 - 3.5 Test case repository version release	At least one new release of new version of test case repository from GitHub repository, including new and updated test cases. Contributes to D3.	Each September, 2023-2027
M4 Dashboard with tested and benchmarked CS	Continuous expansion of the number of tested and benchmarked CS finally leads to a Dashboard showing the final benchmarking. Contributes to D4.	Continuously extending until December 2027

Supporting IBPSA goals (*this position paper*)

The proposed project supports IBPSA goals established by Propositions 0, 1, 13, 14, 15, and 16.

Proposition 0:
The proposed project directly supports this goal by focusing on the evaluation of building control algorithms within individual buildings and in districts using high-fidelity emulators implemented with state-of-the-art building simulation tools.

Proposition 1:
The proposed project directly supports this goal by providing a global forum for discussion and research into state-of-the-art approaches to evaluating new and existing control algorithm performance, as well as subsequent requirements and implementation strategies in necessary simulation technology. The project also provides a platform for embedding the results into publicly available software tools.

Proposition 13:
The proposed project directly supports this goal by developing a publicly available controls performance assessment framework with associated software tools to interface test control algorithms to realistic emulators, benchmark emulator models, and a set of key performance indicators (KPIs) capable of comparing test controller performance. The framework encapsulates assessment procedures through the API functionality of selecting a test case, specifying test scenario parameters, running a test to completion, and reporting KPIs calculated within the framework.

Proposition 14:
The proposed project directly supports this goal by engaging with practitioners who are developing new control strategies and deployment processes and using BOPTEST to de-risk their implementation through simulation-based testing.

Proposition 15:
The proposed project supports this goal by providing easily-deployable realistic building emulators with control and sensor interfaces, which could be incorporated into education and training curriculum through hands-on exercises or demonstrations. Such activities could target students learning controls design, facility operation, and system commissioning.

Proposition 16:
The proposed project supports this goal by providing a framework to facilitate the development and deployment of new control systems that promote optimal building operation, respond to dynamic operational objectives, and are resilient to system faults.

Implementation

Participation is primarily envisioned to include software development, including methods research, code implementation, code testing, and test case creation, as well as CS benchmarking using BOPTEST and Project administration.

Three participation levels are envisioned, to be approved annually by the operating agent(s):

- **Sponsor**: Participants or organizations that fund the Project with cash contribution at US-$ 5,000 per year. This membership will be valid for one year, and can be renewed for multiple periods. Contributions are to be paid to the Treasurer of IBPSA World. Finances are managed by the IBPSA and when the Project terminates, all remaining funds will be owned by IBPSA. Funding will be applied to items such as expenses for in-person expert meetings, such as for rooms, food, A/V, and student travel scholarship, as well as for continuous integration testing, such as for GitHub, travis, or similar.
- **Organizational**: Organizations such as companies, research institutes, or universities that commit to contribute a minimum of 6 months of a full-time employee per project year to the overall project 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 in the Project as is custom in other open-source projects without a predetermined level of commitment.

Meetings will be coordinated both in-person and virtual. Two-day expert meetings will occur in person (if the global context allows) semi-annually, while monthly virtual meetings will be held to maintain task progress. The semi-annual expert meetings will be used to coordinate current work and to steer future development. To the extent possible, these expert meetings will be co-located with international or national IBPSA (or Modelica) conferences. The monthly progress meetings will be organized such that an initial portion (e.g. 1 hour) will be subdivided into parallel, task-specific meeting groups, while the final portion (e.g. 1⁄2 hour) will be used to summarize outcomes of each task and further coordinate among tasks as needed.

The IBPSA GitHub account will be used to host GitHub repositories and project homepage (i.e. through GitHub Pages).

Access and IPR

All workshops, software, and documentation developed under this Project will be open accessible to anyone. To ensure open collaboration among the participants, all code implemented for this Project will be released as open-source using the BSD 3-Clause License as stated at https://github.com/ibpsa/project1-boptest/blob/master/license.md. IBPSA will be the copyright owner. The liberal nature of the license allows others to implement the code in their software and distribute it to others at no cost. Hence, IBPSA ownership of the copyright will allow others to reuse and distribute the software. “IBPSA Test Cases” as described in Task 3 will be contributed according to these license and copyright terms. See Task 3 for terms of “Non-IBPSA Test Case” development.

Risks

Risk	**Mitigation**
No adoption by control developers nor industry.	Community engagement will aid in collecting feedback on needed development.
No project funding available for organizations to participate (a yearly 6 person-month contribution is expected)	Participants are stimulated to include BOPTEST work in new project proposals and student projects, while outreach and community building will increase the relevance and visibility of the work.

IBPSA duties

IBPSA will administer the funds of the Project. If the Project receives 3rd party sponsorship, 10% of the received funds will remain with IBPSA to compensate for overheads, and the other 90% can be used by the Project to cover expenses at the discretion of the operating agent(s). When the Project terminates, all remaining funds will be owned by IBPSA.

As the IBPSA Project 1 has excess funds that will flow to IBPSA when IBPSA Project 1 finishes, IBPSA will provide initial funds to the Project of USD-4,000. If the Project’s funds are depleted, upon approval by the IBPSA Board or its designated delegate:

- IBPSA shall contribute funding to cover expenses for in-person coordination meetings, such as for rooms, food, and A/V.
- IBPSA shall contribute funding to use services for continuous integration testing such as GitHub, travis, or similar.

References

[Arr20] Arroyo, J., Spiessens, F., and Helsen. L. (2020). Identification of Multi-zone Grey-box Building Models for Use in Model Predictive Control. *Journal of Building Performance Simulation* 13 (4): 472–486.

[Arr22] Arroyo, J., Manna, C., Spiessens, F., and Helsen, L. (2022). Reinforced model predictive control (RL-MPC) for building energy management. *Applied Energy* 309: 118346.

[ASH11] ANSI/ASHRAE (2011). ANSI/ASHRAE Standard 140-2011. Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. ASHRAE, Atlanta, GA.

[Blu21] Blum, D., Arroyo, J., Huang, S., Drgona, J., Jorissen, F., Walnum, H. T., Chen, Y., Benne, K., Vrabie, D., Wetter, M., and Helsen, L. (2021). Building Optimization Testing Framework (BOPTEST) for Simulation-Based Benchmarking of Control Strategies in Buildings. *Journal of Building Performance Simulation*, 14(5), 586-610.

[Bun21] Bünning, F., Pfister, C., Aboudonia, A., Heer, P., and Lygeros, J. (2021). Comparing Machine Learning Based Methods to Standard Regression Methods for MPC on a Virtual Testbed. *In Proceedings of the 17th IBPSA Conference*, Sep 1 - 3. Bruges, Belgium.

[Drg20] Drgoňa, J., Arroyo, J., Cupeiro Figueroa, I., Blum, D., Arendt, K., Kim, D., Ollé, E. P., Oravec, J., Wetter, M., Vrabie, D. L., and Helsen, L. (2020). All you need to know about model predictive control for buildings. *Annual Reviews in Control*, 50, 190–232.

[Hua18] Huang, S., Chen, Y., Ehrlich, P. W., and Vrabie, D. L. (2018). A Control-Oriented Building Envelope and HVAC System Simulation Model for a Typical Large Office Building. In *Proceedings of 2018 Building Performance Modeling Conference and SimBuild co-organized by ASHRAE and IBPSA-USA*, Sep 26 - 28. Chicago, IL.

[Jud95] Judkoff, R. and Neymark, J. (1995). International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method. Technical Report NREL/TP-172-6231, NREL, Golden, CO. Available online: http://www.nrel.gov/docs/legosti/old/6231.pdf.

[Ope22] OpenAI (2022). Gym. Available online: https://gym.openai.com.

[Mit22] Mittelmann, H. D. (2022). Decision Tree for Optimization Software. Available online: http://plato.asu.edu/guide.html.

[Wal20] Walnum, H. T., Sartori, I., and Bagle, M. (2020). Model Predictive Control of District Heating Substations for Flexible Heating of Buildings. In *SINTEF Proceedings no 5, ser. BuildSim-Nordic 2020*, Oct 13–14. Oslo, Norway: International Conference Organised by IBPSA-Nordic, 123–130.

[Wan20] Wang, Z., and Hong, T. (2020). Reinforcement Learning for Building Controls: The Opportunities and Challenges. *Applied Energy* 269: 115036.

[Yan20] Yang, T., Filonenko, K., Arendt, K., and Veje, C. (2020). Implementation and Performance Analysis of a Multi-Energy Building Emulator. In *2020 6th IEEE International Energy Conference (ENERGYCon)*, Sep 28 - Oct 1. Gammarth, Tunisia, 451–456.

[Zan22] Zanetti, E., Kim, D., Blum, D., Scoccia, R., and Aprile, M (2022). Performance Comparison of Quadratic, Nonlinear, and Mixed Integer Nonlinear MPC Formulations and Solvers on an Air Source Heat Pump Hydronic Floor Heating System. *Journal of Building Performance Simulation*. https://doi.org/10.1080/19401493.2022.2120631.