Final report

1. Project details

Project title	IBPSA Project 1 Deltagelse
File no.	64018-0518
Name of the funding scheme	EUDP
Project managing company / institution	University of Southern Denmark, SDU Center for Energy Informatics
CVR number (central business register)	29283958
Project partners	-
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2. Summary

English version

Denmark is one of the leading countries in terms of sustainable energy sources, smart grids, and innovative district heating systems. The Center for Energy Informatics (CEI), University of Southern Denmark, has rapidly acquired extensive expertise in modeling, optimization and control of technologies within these topics over the last number of years. Such progress would not be possible without a solid collaboration with international leaders in these fields.

The overall objective of the proposed project is to participate in the international network project, IBPSA Project 1, to foster collaboration with highly renowned international partners in the field of building modeling and simulation.

IBPSA Project 1 “BIM/GIS and Modelica framework for building and community energy system design and operation” is the first project conducted under the umbrella of the International Building Performance Simulation Association. The project aims to create open-source software that builds the basis of next-generation computing tools for the design and operation of building and district energy and control systems.

The project builds upon the knowledge and tools developed within IEA Annex 60 and focuses on the development of open source, standardized, and flexible building and district heating modeling tools based on Modelica. The capabilities of the tools are demonstrated through real live applications that are enabled through Modelica and the Functional Mock-Up Interface (FMI).

The results of the project are already being used in the building modeling and controls community and extension of the network for continuing the work is currently in the making.

Danish version

Danmark er blevet førende omkring bæredygtig energi, smartgrid og innovative fjernvarmesystemer. Center for Energy Informatics (CEI), Syddansk Universitet, har inden for de seneste 5 år etableret en solid forsknings-ekspertise omkring modellering, optimering og styring af teknologier inden for disse emner. En sådan hurtig forskningsopbygning og forskningsmæssige fremskridt ville ikke være muligt uden et solidt samarbejde med ledende internationale forskningscentre på disse områder.

Hovedformålet med det foreslåede projekt er at deltage i det internationale netværksprojekt, IBPSA Project 1, for at fremme samarbejde med højt anerkendte internationale partnere inden for modellering og simulering af energi i bygninger.

IBPSA Project 1 "BIM/GIS and Modelica framework for building and community energy system design and operation" er første projekt, der gennemføres under organisationen International Building Performance Simulation Association (IBPSA). Projektets mål er at skabe open source-software, som danner grundlag for næste generations beregningsværktøjer til design og drift af bygning og energi- og kontrolsystemer.

Projektet bygger videre på den viden og de værktøjer, der er udviklet i IEA Annex 60 (som CEI deltog i) og fokuserer på udvikling af et open source, standardiseret og fleksibelt værktøj til bygning og fjernvarme modellering baseret på Modelica. Funktionerne i værktøjerne skal demonstreres gennem anvendelse af i Modelica og Functional Mock-Up Interface (FMI) i live test studier.

Resultaterne af projektet bruges allerede i bygningsmodellerings- og styringsmiljøet, og en ansøgning til videreførelse af netværket for at fortsætte arbejdet er i øjeblikket under udarbejdelse.

3. Project objectives

The focus of the project was to participate in the international network project, IBPSA Project 1, to foster collaboration with highly renowned international partners in the field of building modeling and simulation.

The objectives, tasks, and specific work packages of IBPSA project 1 were described as follows:

IBPSA Project 1 – General project formulation:

IBPSA Project 1 aims to create open-source software that builds the basis of next-generation computing tools for the design and operation of building and district energy and control systems. The project goals were:

1) To consolidate the development of these technologies, ranging from equipment to system representations of the data (BIM/GIS) and their dynamic behavior (Modelica),
2) To share efforts for, and increase the range of, model validation, and
3) To provide to simulation tool providers stable, well-tested, validated, and documented code that they can integrate in their software tools for deployment to design firms, energy service companies, equipment, and control manufacturers,
4) To demonstrate through applications capabilities that are enabled through Modelica, and to identify and test through applications research needs and research results.

The work was organized in three tasks as follows:

1) Task 1: Further development of the open-source infrastructure of models and test suite to coordinate Modelica-based model developments for building and district energy system design and operation.
2) Task 2: Tool-chains that link object-oriented CAD systems, geoinformation systems, building and control design tools at various levels of detail with Modelica models, and that allow the deployment of these models to real-time systems in support of building commissioning, building controls and fault detection and diagnostics.
3) Task 3: Application, demonstration and dissemination of work conducted in Task 1 and 2.

SDU - Center for Energy Informatics specific contributions:

SDU-CEI has contributed to the following activities within the specific work packages of IBPSA project 1:

WP 1.2 Library for Model Predictive Control

Task 1: Development of Modelica library for Model Predictive Control

Task 2: Development of BOPTEST – open-source Building Optimization Test framework

Task 3: Development of different Model Predictive Control formulations; CEI contributes with two: (1) Multi-Objective Genetic Algorithm (MOGA), (2) Multiple Shooting Method

Task 4: Benchmarking of the MPC formulations using BOBTEST - Activity for extending MPC from buildings to networks in relation to WP 3.1

WP 3.1 Application

Task 1: Development of the Termonet library, the Modelica library for modeling, validation, and optimization of electric, thermal, and hydronic grids in small-scale district heating (<100 households)

Task 2: Validation of the IBPSA district heating models and Termonet library (DESTEST framework) against experimental data ('Energy Living Lab - Vejle Nord' project)

Task 3: Statistical and economic analysis and grid balancing with IBPSA/Termonet libraries

WP 3.2 Dissemination

In general, all partners contributed to WP 3.2 with publications according to the WP description. In addition, SDU-CEI contributed to bachelor and master projects in WP 3.1 and Modelica teaching at the master or bachelor level.

Task 1: Submission of 4 Publications

Task 2: Participation in 4 Conferences

Task 3: InnoSE Seminar - Vejle Nord Living Lab

Task 4: Danish IBPSA Final Seminar

4. Project implementation

SDU-CEI participated in the work of WP1 and WP3 within the IBPSA Project 1. There was no SDU-CEI contribution to WP 2. The work was coordinated through bi-annually project expert meetings and monthly work package meetings.

The following expert meetings took place during the reported project period:

- 3rd expert meeting, April 3-4, 2019, Aachen, Germany
- 4th expert meeting, August 31-September 1, 2019, Rome, Italy
- 5th expert meeting, May 6-7, 2020, online
- 6th expert meeting, October 13-14, 2020, online
- 7th expert meeting, May 7 and May 12, 2021, online
- 8th expert meeting, October 18 and November 15, 2021, online
- 9th expert meeting, March 28 and March 30, 2022, online

The expert meetings included an overview presentation of the IBPSA project 1 deliverables and achievements to both already involved and potential project participants to broaden collaborations internationally. The overview presentation was followed by individual work package breakout sessions, where in-depth discussions took place on the work package's current status, future directions, and technical issues. In addition to expert meetings, each work package subtask leader held regular online work meetings monthly to check updates, discuss technical issues, and distribute detailed work tasks for the following month. Bilateral meetings between individual project partners were organized based on the need for collaboration for the work tasks.

The project progressed in accordance with the plan. At the time of writing this final report, the defined task's milestones have been completed. The Covid pandemic has challenged the project as physical expert meetings are of high importance. Online versions have been conducted and we have managed to keep good collaboration with an increased effort in having online and more frequent WP meetings.

5. Project results

In accordance with the SDU-CEI specific contributions defined in Section 3, the results of the project are detailed under each work package and task as indicated below:

Project results for WP 1.2 Library for Model Predictive Control

Task 1: Development of Modelica library for Model Predictive Control

A Modelica-based library for building zone models (Package name "OU44") was developed for model predictive control applications. The models were validated against on-site measurements and tested within model predictive control frameworks (Mshoot and Controleum)

Task 2: Development of BOPTEST – open-source Building Optimization Test framework

An emulator for a university teaching building consisting of a hydronic heating loop and CO_2-driven ventilation unit has been developed and validated against measurements from on-site sensor data collections. The unit tests of the emulator for BOPTEST were conducted and went through, the emulator is ready for BOPTEST and has been merged to the BOPTEST repository, allowing potential users to test their control strategies on. Additionally, SDU-CEI has contributed to reviewing the emulator developed by Engie.

Task 3: Development of different Model Predictive Control formulations; CEI contributes with two: (1) Multi-Objective Genetic Algorithm (MOGA), and (2) Multiple Shooting Method.

Two model predictive control frameworks were developed, namely Controleum—A multi-objective MPC framework for buildings, and Mshoot—A multiple shooting method-based MPC framework for buildings. The two developed frameworks enable users to implement model predictive control strategies for buildings, and to compare different MPC formulations using either a genetic algorithm or multiple shooting method.

Task 4: Benchmarking of the MPC formulations using BOBTEST - Activity for extending MPC from buildings to networks in relation to WP 3.1

The MPC formulation using BOPTEST was discussed extensively within the subtask monthly work meetings. A tutorial on MPC formulation using BOPTEST was created and offered to a broader audience of interest at the workshop of Building Simulation Conference 2021. The MPC formulation using BOPTES was benchmarked by applying it to different test cases –- a single-zone air-based commercial building and a multi-zone hydronic residential building.

Project results for WP 3.1 Application

Task 1: Development of the Termonet library, the Modelica library for modeling, validation, and optimization of electric, thermal, and hydronic grids in small-scale district heating (<100 households)

The development of Modelica library Termonet was completed and available for public use. This library is a valuable asset for modeling, validation, and optimization of electric, thermal, and hydronic grids in small-scale district heating.

Task 2: Validation of the IBPSA district heating models and Termonet library (DESTEST framework) against experimental data ('Energy Living Lab - Vejle Nord' project)

The IBPSA district heating models and Termonet library were validated through proposed common exercises under the DESTEST framework. The model validation was carried out against experimental data from the 'Energy Living Lab - Vejle Nord' project, creating the synergies between two different projects.

Task 3: Statistical and economic analysis and grid balancing with IBPSA/Termonet libraries

Three case studies indicated below were developed:

- MPC-oriented models of a small district with geothermal heat pumps
- Dimensioning of IBPSA plug flow pipes for Vejle Nord Live Lab using Dymola FMI and Python
- Verification of district heating Modelica components for renewable integration

The developed three case studies were built upon IBPSA and Termonet Modelica libraries, enabling the statistical and economic analysis and grid balancing of different energy systems.

Project results for WP 3.2 Dissemination

The work in SDU-CEI IBPSA project 1 participation has been disseminated through bi-annual project expert meetings, monthly work package coordination meetings, journal publications, conference participations, seminars, and workshops. In addition, the research outcomes of this project were utilized for bachelor's and master's teaching activities. The main publication deliverables for dissemination of SDU-CEI participation in IBPSA project 1 are listed in Section 8.

6. Utilisation of project results

Buildings and district energy networks are an integrated part of the distribution and demand side of the energy system. With the increasing integration of renewable energy production, there is a continuing need for the demand side to reduce energy and peak consumption while securing customer and occupant satisfaction. The high complexity of these systems requires holistic and optimal design and operation, in order to be socioeconomically relevant. This need continuously drives the development of building and energy system simulation programs suitable for decision-making during the building and energy system design, commissioning, and operation stages. However, these tools and modeling approaches are poorly integrated and therefore, hinder not only energy and comfort performance analysis in the design stage, but also limit the potential of using advanced model-based control strategies in buildings, e.g., model predictive control. To address these challenges the integration process should be based on open and flexible standards, like IFC, CityGML, and Modelica.

IBPSA Project 1 “BIM/GIS and Modelica framework for building and community energy system design and operation” is the first project conducted under the umbrella of the International Building Performance Simulation Association. The project aim was to create open-source software that builds the basis of next-generation computing tools for the design and operation of building and district energy and control systems.

The project advanced the state of the art by developing an integrated approach for building information and performance modelling, as well as design and control optimization.

The outcomes of the IBPSA Project 1 have enabled bridging the gap between Building Information Models (BIM), Geography Information Models (GIS), and Building Performance Models (BPM). By doing so it contributed to improving energy and comfort performance in buildings, districts, and cities. In addition, the tools developed in the project may constitute the basis of ICT business-oriented solutions.

SDU-CEI participation in IBPSA Project 1 has involved academic staff at all levels, from Ph.D. to Professor level. More specifically from Danish side Ph.D. students, postdocs and assistant professors have contributed to the specific subtasks in this project. In addition to scientific publications, the project results were the fundamentals for course materials at SDU bachelor's and master's levels for the Energy Technology program.

7. Project conclusion and perspective

With respect to the overall aim and the specific objectives, SDU-CEI IBPSA Project 1 participation has:

- Developed a Modelica library for model predictive control applications.
- Developed different model predictive control formulations: (1) multi-objective genetic algorithm (MOGA), (2) multiple shooting method.
- Developed a building emulator for BOPTEST and contributed to benchmarking of the MPC formulations using BOBTEST.
- Developed, and validated a Modelica library for modeling, validation, and optimization of electric, thermal and hydronic grids in small-scale district heating. The library has been utilized in three different energy systems to support application cases.
- Disseminated project results through various forms of activities including bi-annual project expert meetings, monthly work package coordination meetings, journal publications, conference participations, seminars, workshops, and bachelor and master teaching activities.

IBPSA project is, therefore, considered as a major step forward in acquiring extensive expertise in the field of building and community energy system modeling, simulation, and control, and enhancing collaborations both nationally and internationally.

At the time of writing this final report, all the tasks and milestones defined in SDU-CEI participation of the project have been completed. Over the project period (2019-2022), plenty of deliverables have been achieved consisting of numerous publications, two Modelica libraries, MPC development, many conference participations, project coordination meetings, etc. It can be concluded that this project has advanced the knowledge of building modeling and simulation and fostered collaboration with international partners, which fulfills the overall objectives of the project.

8. Appendices

Conference paper publications

[1] Arendt, Krzysztof, Muhyiddine Jradi, Hamid Reza Shaker, and Christian Veje. "Comparative analysis of white-, gray-and black-box models for thermal simulation of indoor environment: Teaching building case study." In Proceedings of the 2018 Building Performance Modeling Conference and SimBuild co-organized by ASHRAE and IBPSA-USA, Chicago, IL, USA, pp. 26-28. 2018.

[2] Arendt, Krzysztof, Muhyiddine Jradi, Michael Wetter, and Christian T. Veje. "Modestpy: An open-source python tool for parameter estimation in functional mock-up units." In Proceedings of the American Modelica Conference. 2018.

[3] Arendt, Krzysztof, and Christian T. Veje. "MShoot: An Open-Source Framework for Multiple Shooting MPC in Buildings." In 16th IBPSA International Conference and Exhibition Building Simulation. 2019.

[4] Yang, T., Filonenko, K., Arendt, K., & Veje, C. Implementation and performance analysis of a multi-energy building emulator. In Proceedings of 6th IEEE International Energy Conference 2020.

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[6] Filonenko, K., Gammelgaard, E., Hansen, D., Buck, J., & Veje, C. Verification of multi-energy system components for renewable integration. In Proceedings of the 6th IEEE International Energy Conference.

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[13] Hicham, J., Mans, M., Filonenko, K., De Jaeger, I, Saelens, D., Tvedebrink, T. (Accepted/In press). Evaluating different metrics for inter-model comparison of urban-scale building energy simulation time series. Proceedings of Building Simulation 2021: 17th Conference of. https://bs2021.org.

[14] Filonenko, K., Copeland, M., Jespersen, K., & Veje, C. (2020). Modeling future heat pump integration in a power radial. I M. Tiller, H. Tummescheit, L. Vanfretti, C. Laughman, & M. Wetter (red.), Proceedings of the American Modelica Conference 2020, Boulder, Colorado, USA, March 23-25, 2020: Linköping Electronic Conference Proceedings (Bind 169, s. 130-138). Modelica Association and Linköping University Electronic Press. Linköping Electronic Conference Proceedings https://doi.org/10.3384/ECP20169130.

[15] Yang T, Veje C. Analysis and Application of Model Predictive Control in Energy Systems. In the Ph.D. workshop of 1st Energy Informatics.Academy Asia Conference. 2021.

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Journal paper publications

[17] Blum, D. H., K. Arendt, L. Rivalin, M. A. Piette, M. Wetter, and C. T. Veje. "Practical factors of envelope model setup and their effects on the performance of model predictive control for building heating, ventilating, and air conditioning systems." Applied Energy 236 (2019): 410-425.

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Course project, master thesis and Ph.D. thesis

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[22] Søndergaard, M. V., Christiansen, S. W. (2022). Microgrid Simulation in Dymola. Course project report. University of Southern Denmark, Odense, Denmark.

[23] Sorensen, A. G., Helt, M. B., Gregersen, M. E. (2022). Designing and Modeling of a Combined Energy

Portfolio Consisting of Photovoltaic Electricity and Electrolytic Hydrogen Production. Course project report. University of Southern Denmark, Odense, Denmark.

[24] Nielsen, E. W., Skjodt, E. G., Christensen, J. S. (2022). House HVAC System Simulation in Dymol. Course project report. University of Southern Denmark, Odense, Denmark.

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[26] Fouquet, D. (2022). Solar Panel Modeling. Course project report. University of Southern Denmark, Odense, Denmark.

[27] Pedersen, J. M., Kirketerp, M. (2021). Dymola introduction of an electric vehicle with vehicle-to-grid functionalities. Course project report. University of Southern Denmark, Odense, Denmark.

[28] Pedersen, A. S. H., Meyer, L., Ustrup., S. E. (2021). Grey-box model of a residential wind-battery energy system. Course project report. University of Southern Denmark, Odense, Denmark.

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[32] Copeland, M., & Jespersen, K. (2019). Modeling of the future distributed electricity grid. Master Thesis. University of Southern Denmark.

[33] Gammelgaard, E., & Hansen, D (2020). Object-oriented modeling and flexibility study of a district heating network for smart energypuljen in Vejle Nord Live Lab. Master Thesis. University of Southern Denmark.

[34] Camilla Juel Gammelby (2019). DC-DC converter Modeling using Dymola and State Space Approach. Individual study report at SDU Energy Technology master program.

[35] Jonas Fausing Olesen (2019). The HVAC System of Building OU44. Individual study report at SDU Energy Technology master program.

[36] Morten Hagenau (2019). Occupancy model. Individual study report at SDU Energy Technology master program.

[37] Daniel Anthony Howard (2019). Magnetocaloric Heat Pump Implementation for District Heat-ing. Individual study report at SDU Energy Technology master program.

[38] Elisabeth Keller (2019). Modelling District Heating in Modelica. Individual study report at SDU Energy Technology master program.

GitHub

[39] Modelica Library for MPC, https://github.com/sdu-cfei/OU44.

[40] OU44 Emulator, https://github.com/ibpsa/project1-boptest/tree/master/testcases/singlezone_commercial_hydronic

[41] Termonet Library, https://gitlab.sdu.dk/termonet/termonetlibrary.

[42] https://github.com/ibpsa/project1

Other Links

[43] https://ibpsa.github.io/project1/publications.html

[44] https://github.com/ibpsa/project1-boptest/tree/master/docs/workshops/BS21Workshop_20210831