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IBPSA Project 1: BIM/GIS and Modelica framework for building and community energy system design and operation – ongoing developments, lessons learned and challenges

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IBPSA Project 1 : BIM/GIS and Modelica framework for building and community energy system design and operation – ongoing developments, lessons learned and challenges

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Abstract. IBPSA Project 1 develops and demonstrates an open-source BIM/GIS and Modelica Framework for building and community energy system design and operation. The project builds further on the completed project IEA EBC Annex 60 "New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards." This paper describes the motivation and approach of the project, and it provides an update about recent activities. These activities include development of a core Modelica library for building and community energy systems; development of BOPTEST, a virtual test bed to test advanced controllers such as MPC; development of GIS/BIM data model translators for Modelica; development of new workflows for improved productivity and quality assurance of urban-scale energy simulation; and development of DESTEST, a validation test for district energy models.

1. Introduction

In the building energy modeling community, there is a need to standardize the approach for how component and system models are represented, both as data-model and as mathematical models that formalize the physics, dynamics and control algorithms. This is required to agree upon the physics that should be included in such components for specific use cases, and to share resources for development, validation and distribution of such component and system models; at scales ranging from individual components, through buildings to communities of buildings. There is also a need for a consolidation of models for HVAC and controls that can be used for testing [1]. Similar objectives have been shared by IEA EBC Annex 60, a project in which 41 institutes from 16 countries participated between 2012 and 2017 [2]. Annex 60 developed and demonstrated new computational technologies based on the open standards Modelica [3], used as a modeling language, Functional Mockup Interface (FMI) [4], used to



exchange legacy models or simulators, and Industry Foundation Classes (IFC) [5], used to represent Building Information Models (BIM). A recent study has shown that the FMI standard is considered as the most promising standard for co-simulation [6]; furthermore, recent studies have shown that equation-based languages such as Modelica have many advantages for simulating and optimizing buildings and district energy systems over state of the art modeling languages based on causal modeling approaches [7], [8].

A subset of the Annex 60 work is now continued under the umbrella of the International Building Performance Simulation Association (IBPSA). This continuation is conducted within the IBPSA Project 1 "BIM/GIS and Modelica framework for building and community energy system design and operation." It is conducted from summer 2017 to summer 2022.

The objective of this paper is to report on the current status and future developments of this project. The paper is structured as follows: In Section 2 we summarize the challenges and in Section 3 we summarize the goals and structure of the Project 1. The challenges and goals are based on the IEA EBC Annex 60 final report, as they remain unchanged since its publication and provide the motivation for IBPSA Project 1. In Section 4 we discuss ongoing developments within the project, and in Section 5 we present concluding remarks.

2. Challenges

To meet increasingly stringent energy performance targets and challenges posed by distributed renewable energy generation in the building and district energy community, recent attention has been given to system-level integration of thermal, electrical, control and communication systems as well as to operational optimization of buildings. The intent is to design and operate a building or a neighborhood optimally as a performance-based, robust system that can shed and shift demand, storage and production across energy carriers to provide flexible loads. This requires taking into account system-level interactions between thermal (including the building fabric) and electrical storage, electrical appliances, HVAC and renewable energy systems and the electrical and thermal grids. Such a system-level analysis requires multi-physics and multi-scale simulation and optimization using coupled thermal, electrical, behavioural and control models. Optimal operation also requires closing the gap between designed and actual performance through commissioning, energy monitoring and fault detection and diagnostics. All of these activities can benefit from using models that represent the design intent. These models can then be used to verify responses of installed equipment and control sequences, and to compute optimal control sequences in a Model Predictive Controller (MPC), the latter of which possibly requiring simplified models.

Furthermore, in the AEC domain the processes of designing, constructing and commissioning buildings and energy systems are rapidly changing toward digitalization. BIM and City Information Modeling (CIM) [9] is an enabler as collaborative method and tool to consistently gather, manage and exchange building- and infrastructure-related data on a digital basis over the entire life cycle of a facility. BIM/CIM are not a specific software, it is rather a method as part of, but not limited to, the integral design. A truly added value is expected for the near future when design and commissioning in the sense of computer aided facility management comes together. The above mentioned issues of commissioning, energy monitoring and fault detection and diagnostics can therefore highly benefit from a thorough digital planning when location and function of technical systems are together referenced in a digital model, when the as-built state is harmonized with and well documented in a model and when home and building automation becomes integrally linked with BIM. This shift in focus will require an increased use of models throughout the building delivery stages and continuing into the operational phase. It also gives rise to new requirements for building and urban simulation tools, including the following:

- Mechanical engineers should be able to design, assess the performance and verify the correctness of local and, in particular, supervisory control sequences in simulation. They should then use such a verified, non-ambiguous specification to communicate their design intent to the control provider

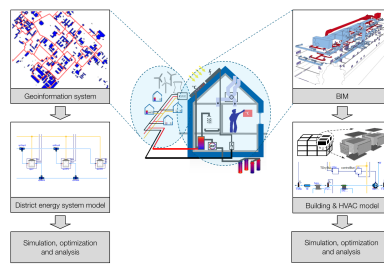


Figure 1. Overview of the scope of IBPSA Project 1.

[10]. Moreover, the specification should be used during commissioning to verify that the control contractor implemented the design intent.

- Controls engineers should be able to extract subsystem models from models used during the building design in order to use them within building control systems for commissioning, model-based controls, fault detection and diagnostics.
- Urban planners and researchers should be able to combine models of buildings, thermal and electrical grids and controls in order to improve the design and operation of such systems to ensure low greenhouse gas emissions or costs, and high quality power delivery [7].
- Mechanical engineers should be able to convert design models to a form that allows the efficient and robust solution of optimal control problems as part of MPC [11]. Such models may then be combined with state estimation techniques that adapt the model to the actual building [12].

The first item requires modeling and simulation of actual control sequences, including proper handling of hybrid systems, i.e., systems in which the state evolves in time based on continuous time semantics that arises from physics, and discrete time and discrete event semantics that arises from digital control [13]. This poses computing challenges for the deterministic synchronization of these domains [14]. The second item requires extraction of a subsystem model and exporting this model in a self-contained form that can readily be executed as part of a building automation system as shown in [15]. The third item requires models of different physical domains and models of control systems to be combined for a dynamic, multi-physics simulation that involves electrical systems, thermal systems, controls and possibly communication systems, which may evolve at vastly different time scales. The fourth item greatly benefits if model equations are accessible to perform model order reduction and to solve optimal control problems.

3. Goals and organization of the Project 1

Currently fragmented duplicative activities in modeling, simulation and optimization of building and community energy systems are coordinated through the use of the open, non-proprietary standards IFC/CityGML for BIM/CIM representation, and Modelica for model implementation. Figure 1 shows the scope of IBPSA Project 1. There are two thrusts, one for district modeling and one for building modeling. Each thrust is separated into data modeling, modeling of the physics and controls, and simulation, optimization and analysis. Data modeling include standards and transformation algorithms to link object-oriented simulation modeling with building and Geographic Information System (GIS) by adopting standards such as IFC and CityGML. Mathematical modeling include the development and validation of dynamic models that represent the physics and control logic of components and systems. Optimization includes research and benchmarking in model predictive control, and simulation includes validation of component and city quarter models. For the implementation of models for simulation and optimization, the Modelica language is used.

The anticipated outcomes are documented, validated and verified Modelica libraries, and BIM/CIM to/from Modelica translators that allow buildings and community energy systems and grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand. To ensure open collaboration among the participants, all code will be released as open-source using a BSD 3-Clause License. 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. All workshops, software and documentation will be open accessible to anyone. The primary target audience is the building energy research community, students in building energy related sciences, and providers of computing tools for buildings.

The project is organized into three tasks, which are further refined into work packages as follows: Task 1 further develops the open-source infrastructure of models and test suite to coordinate Modelica-based model developments for building and district energy system design and operation. Furthermore, it coordinates research in MPC and it develops a test suite for comparing the performance of advanced control sequences called BOPTEST. Task 2 is developing tool-chains that link object-oriented CAD systems, GIS, building and urban design tools at various levels of detail with one another and with Modelica models. Task 3 is focusing on validation, application, demonstration and dissemination. It includes the development of a validation test for district energy system simulation called DESTEST.

4. Ongoing developments

This section describes the goal, approach and results of the various work packages.

4.1. Task 1

Task 1 develops Modelica and FMI-based software that support the design and operation of buildings and community energy systems. It develops Modelica libraries, coordinates research in MPC, and develops a test for the performance comparison of advanced control approaches.

4.1.1. WP 1.1 Modelica library for design and operation The goal of this work package is to provide a robust, validated and well documented library of Modelica models that serve as the core of Modelica libraries for building and district energy simulation. The approach is to jointly develop the so-called *Modelica IBPSA Library*, hosted at <https://github.com/ibpsa/modelica-ibpsa> and formerly called the *Modelica Annex 60 Library*. The Modelica IBPSA Library is an open-source library that has more than 500 models, blocks and functions [16]. This library serves now as the core of the four Modelica libraries AixLib from RWTH Aachen University in Germany [17], Buildings from LBNL at Berkeley [13], BuildingSystems from UdK Berlin in Germany [18], and IDEAS from KU Leuven in Belgium [19]. These libraries integrate the IBPSA library as their core, add additional models and documentation, and distribute it to their end users. Through this method, the IBPSA library also becomes part of the redesign of EnergyPlus called "Spawn of EnergyPlus" (<https://lbl-srg.github.io/soep/>). Recent activities and results include the addition of models for heat pumps, borefields and glycol solutions, as well as models that allow generating from a Modelica model a building emulator, packaged as a Functional Mockup Unit, for use in the BOPTEST (Building Optimization Performance Test) that is developed in Work Package 1.2 described below. Moreover, models have been further improved and are now fully compatible with the open-source, freely available JModelica simulation environment.

4.1.2. WP 1.2 Model Predictive Control The goal of this work package is to develop a framework that facilitates the formulation of MPC and that allows testing, assessing, comparing and benchmarking MPC formulations. The approach is (1) to jointly develop an open-source library of models that can be used to efficiently solve optimal control problems for building and district energy systems, and that can be combined with parameter and state estimation algorithms; (2) to develop a framework,

called BOPTEST (Building Optimization Performance Test, hosted at <https://github.com/ibpsa/project1-boptest>), to virtually test and assess the performance of controllers, among them MPC. The BOPTEST concept consists of reference building emulation test cases, key performance indicators (KPIs) for quantification and assessment, and a software platform to select and manage test cases, exchange control and measurement data, calculate KPIs and generate reports. The aim of a test case is to provide a clear and unambiguously defined scenario where any controller can be tested to enable a fair comparison between different control strategies. Therefore, a test case is defined as a combination of a building emulator model and a data-set gathering boundary conditions like weather, energy prices, emission factors, occupancy schedules and comfort requirements for a one-year duration, where building location, construction type and HVAC system are consistently aligned. The ten test cases selected represent combinations of buildings and energy systems typically encountered in Europe and the US. Each test case describes the signals that are accessible at different control levels, e.g. room temperature set points at high level, damper positions, fan and pump speeds, flow rates at low level. Baseline controllers are included and operate whenever the control signal is not overwritten by the external (tested) controller. The software platform architecture for deployment and interaction with controllers has been set up. It consists of an emulator pool, a database, a simulation manager and a HTTP Rest API, which is an interface that is independent of the modelling and controller programming languages. The framework is being implemented in Docker containers, and an example test case has illustrated the capabilities of the framework [20].

4.2. Task 2

Task 2 concerns the transformation process from digital district and building information models to simulation.

4.2.1. WP 2.1 City District Information Modeling This work package addresses urban scale energy performance simulation of domestic and non-domestic buildings. Highlighting the exchange requirements and country-specific data mapping approaches, the work package also deals with archetypal definitions of buildings with respect to the generalization of country-specific age-bands, geometrical forms and building functions. Semantic data enrichment, parsimonious geometric information processing and the participation in development of the CityGML schema and EnergyADE for specific simulation tools is also emphasized. Considering different modelling techniques, generic import-export functionalities and enrichment algorithms, the team aims to demonstrate the application of the developed workflows for a range of tools, including Modelica and EnergyPlus, and for a range of geographical contexts and application use cases. The GML ToolBox [21], which extends the pre-processing of geometric prerequisites, modelling of thermal zones and openings and checks CityGML base standards and ADE conformance conditions for dynamic heating and cooling demand simulations in EnergyPlus, is one such example. Another example is an extension to the TEASER [22] tool that is currently being developed to process the five CityGML Levels of Detail and Energy ADE information as an input for annual thermal simulation using Modelica. A further example is the development of a new workflow for the preparation of large (thousands to tens of thousands of buildings) urban scenes for simulation using the CitySim+ urban energy simulation engine [23]. Open source translators and workflows for district energy simulations can be recognized as some of the outputs for this work package.

4.2.2. WP 2.2 BIM The work package starts from the core observations that CAD-integrated calculation and dimensioning requires detailed models and that such models are typically not available in the early design stages. Furthermore, common HVAC classification schemes are lacking, HVAC wiring diagrams, which are relevant for linking with control descriptions, cannot be exchanged with common software, standards are not available for digital function specification exchange and existing BIM software is typically not capable of extracting space boundary descriptions in a way to be used for energy performance simulation using zonal modeling or for CFD approaches for detailed indoor air flow

analysis. The work package therefore addresses such data classification and specification, geometry and HVAC model processing. In the first phase, groundwork was set up for the collaborative development and testing of different classes of geometric algorithms for transforming building information models to building performance simulation. Various libraries were considered for reading IFC data and for processing geometric information such as IfcOpenShell, IfcPlusPlus, xBIM (IFC) as well as the geometry kernels OpenCascade, ParaSolid and ACIS.

Based on this experience, developments will be continued using the IfcOpenShell and OpenCascade libraries. Advanced space boundary algorithms for model topology analysis and model generation are currently tested [24],[25] and new algorithms are developed. Code and models are organized in the IBPSA Project 1 GIT repository. Test cases are collected with contribution from the international consortium in order to set up a robust test bed for the space boundary algorithms. A background software service analyses on an hourly basis the content of the entire repository for IFC files and automatically organizes these test cases in terms of contained entities and structures in a database with interlinked and browsable content. As of today, 54 IFC2x3 and 28 IFC4 test files containing 245 IFC entities are registered.

4.3. Task 3

The aim of Task 3 is to develop a test suite for district energy systems, referred to as the DESTEST, and to demonstrate through applications the capabilities that are enabled through Modelica. These applications will also provide feedback to the technology development in Tasks 1 and 2.

4.3.1. WP 3.1 DESTEST The aim of DESTEST is to provide a means to validate models of urban energy systems by defining specific district energy cases for testing in different simulation environments. By carefully selecting and specifying these cases, and by using different libraries for modeling these energy systems, a thorough verification, comparison and benchmarking will become possible. The description of the DESTEST cases and the simulation results of extensively verified models for urban energy systems will be available as a reference for comparing other simulation programs and model libraries. The first common exercise, a simple case in which the energy demand and the distribution subsystem of a district heating system are modelled, demonstrates how such a DESTEST could be used. The energy demand was modelled with five simulation environments, illustrating the difficulty of modelling the exact same building in different environments. Similarly, the network modelling was also used to compare the output of five network simulation models. Supplementary to this comparison, a simulation study focusing on the performance of solvers was done using one particular model.

In future work other building typologies and characteristics, climate and occupancy patterns as well as districts with different scales will be implemented. With respect to networks, cooling networks and electrical grids will also be analysed. Finally, demand and distribution subsystems will be combined to assess the performance of control actions and to check interoperability of tools that model separate subsystems.

4.3.2. WP 3.2 Application The aim of this work package is to demonstrate capabilities enabled by the use of Modelica for building and district energy systems. This task will be accomplished by gathering a number of case studies and describe them through a unified template that facilitates a systematic comparison and illustrates key findings from different applications. The template includes information such as description of the physical problem, objective of the simulation study, building/district system diagram and advantages and limitations of the use of Modelica. The expected outcome of this work package is a collection of application case studies that aim at sharing best practices and document them for dissemination to the simulation community. The systematic collection of application case studies will further lead to the identification of research needs for Tasks 1 and 2.

5. Conclusions

IBPSA Project 1 covers a wide range from data modeling to simulation of buildings and district energy systems, including detailed feedback control algorithms, performance comparison of control approaches and validation of district energy simulations. The work is based around open standards for data modeling (IFC and CityGML), for modeling of physical and control systems (Modelica) and for exchange of simulators (FMI). The tight collaboration and joint development of technologies among groups from different countries and continents, each funded by their own respective projects, would not have been possible had our work not been based on open standards, as these standards provide a common basis around which research, development and deployment activities can be organized. As such, our intent is that this project provides a strong basis for continued collaborative development of tools that lead to high performance building and district energy solutions.

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