Energy and Buildings xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Equation-based languages – A new paradigm for building energy modeling, simulation and optimization

Michael Wetter*, Marco Bonvini, Thierry S. Nouidui

Lawrence Berkeley National Laboratory, Energy Technologies Area, Building Technology and Urban Systems Department, Simulation Research Group, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 19 July 2015
Received in revised form 7 October 2015
Accepted 8 October 2015
Available online xxx

Keywords:
Equation-based modeling
Modelica
Multi-physics simulation
Smart grid
Optimal control

ABSTRACT

Most of the state-of-the-art building simulation programs implement models in imperative programming languages. This complicates modeling and excludes the use of certain efficient methods for simulation and optimization. In contrast, equation-based modeling languages declare relations among variables, thereby allowing the use of computer algebra to enable much simpler schematic modeling and to generate efficient code for simulation and optimization.

We contrast the two approaches in this paper. We explain how such manipulations support new use cases. In the first of two examples, we couple models of the electrical grid, multiple buildings, HVAC systems and controllers to test a controller that adjusts building room temperatures and PV inverter reactive power to maintain power quality. In the second example, we contrast the computing time for solving an optimal control problem for a room-level model predictive controller with and without symbolic manipulations. Exploiting the equation-based language led to 2200 times faster solution.

Published by Elsevier B.V.

1. Introduction

To meet increasingly stringent energy performance targets and challenges posed by distributed renewable energy generation on the electrical distribution grid, recently more attention is given to system-level integration, part-load operation and operational optimization of buildings. The intent is to design and operate a building or a neighborhood optimally. This requires taking into account system-level interactions between building storage, HVAC systems and electrical grid. Such system-level analysis requires multi-physics simulation and optimization using coupled thermal, electrical 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 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 possibly after simplifying the model.

This shift in focus will require an increased use of models throughout the building delivery stages and continuing into the operational phase. For example, during design, a mechanical engineer will construct a model that represents the design intent. To reduce cost for implementation of the control sequence, and to ensure that the control intent is properly implemented, a control model could be used to generate code that can be uploaded to supervisory building automation systems, thereby executing the same sequence as was used during design [1]. During commissioning, the design model will be used to verify proper installation. During operation, the model will be used for monitoring actual with expected energy use [2], and for fault detection and diagnostics [3]. Also, model calibration offers an opportunity to diagnose why performance as-designed and as-installed differ. Furthermore, the model can be converted to a form that allows its use during operation as part of a MPC algorithm.

In addition to the focus on closing the performance gap between design and operation, another recent focus is to evaluate how building dynamics, HVAC, thermal and electrical storage, renewable energy generation and grid responsive control affect the electrical grid [4,5]. Models that integrate building loads, HVAC and electrical systems can be used to develop control sequences that attempt to ensure power quality.

For a larger discussion of functionalities that future building modeling tools will need to provide to address the needs for low energy building and community energy grid design and operation, we refer to [6,7].

---

* Corresponding author.
E-mail address: MWetter@lbl.gov (M. Wetter).

http://dx.doi.org/10.1016/j.enbuild.2015.10.017
0378-7788/Published by Elsevier B.V.

Please cite this article in press as: M. Wetter, et al., Equation-based languages – A new paradigm for building energy modeling, simulation and optimization, Energy Buildings (2015), http://dx.doi.org/10.1016/j.enbuild.2015.10.017

Nomenclature

Symbol	
$\mathbb{R}^n$	Euclidean space of n-tuples of real numbers
$f(\cdot)$	function, with the dot standing for the undesignated variable
$f(x)$	value of $f(\cdot)$ evaluated for the variable x
$f: A \to B$	function with domain in space A and range in space B
$x \in A$	x is an element of space A
$\dot{x}(\cdot)$	time derivative of variable x

For the aforementioned new foci, the following new needs are emerging for building simulation tools:

1. 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. Moreover, the specification should be used during commissioning to verify that the control contractor implemented the design intent.
2. 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.
3. Urban planners and researchers should be able to combine models of buildings, electrical grids and controls in order to improve the design and operation of such systems that ensure high performance in terms of greenhouse gas emissions or cost, while ensuring power quality of the grid [4,5].
4. 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 [8]. Such models may then be combined with state estimation techniques that adapt the model to the actual building [3].

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. 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. 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. The fourth item greatly benefits if model equations are accessible to perform model order reduction and to solve optimal control problems. In this paper, we will focus on the third and fourth items. For the first and second items, see [9,10] and [1], respectively.

The contributions of this paper are (i) to explain how equation-based languages for multi-physics systems can address needs for design, operation and dynamic analysis of low energy systems coupled to reneweable energy generation and transmission, (ii) to show how Modelica models for building envelope, generated from OpenStudio input files, can be linked to Modelica models for HVAC and electrical systems to develop a controller that adjusts building temperature and PV inverter reactive power to maintain power quality, and (iii) to show how Modelica models can be used to efficiently solve optimal control problems that minimize energy use subject to comfort constraints.

2. Comparison to state-of-the-art in building energy modeling and simulation

Today's whole building simulation programs formulate models using imperative programming languages. Imperative programming languages assign values to functions, declare the sequence of execution of these functions and change the state of the program, as is done for example in C/C++, Fortran or MATLAB/Simulink. In such programs, model equations are tightly intertwined with numerical solution methods, often by making the numerical solution procedure part of the actual model equations. This approach has its origin in the seventies when neither modular software approaches were implemented nor powerful computer algebra tools were available. These programs have been developed for the use case of building energy performance assessment to support building design and energy policy development. Other use cases such as control design and verification, model use in support of operation, and multiphysics dynamic analysis that combines building, HVAC, electrical and control models were no priorities or not even considered [11]. However, they recently gained importance [7].

Tight coupling of numerical solution methods with model equations and input/output routines makes it difficult to extend these programs to support new use cases. The reason is that this coupling imposes rules that determine for example where inputs to functions that compute HVAC, building or control equipment are received from the internal data structure of the program, when these inputs are updated, when these functions are evaluated to produce new output, and what output values may be lagged in time to avoid algebraic loops. Such rules have shown to make it increasingly difficult for developers to add new functionalities to software without inadvertently introducing an error in other parts of the program. They also make it difficult for users to understand how component models interact with other parts of the system model, in particular their interaction with, and assumptions of, control sequences. Furthermore, they also have shown to make it difficult to use such tools for optimization [12].

The tight coupling of numerical solution methods with model equations makes it also difficult to efficiently simulate models for the various use cases, the reason being that the numerical methods in todays' building energy simulation programs are tailored to the use case of energy analysis during design. However, other use cases such as controls design and verification, coupled modeling of thermal and electrical systems, and model use during operation require different numerical methods. To see why different numerical methods are required, consider these applications:

Stiff systems: The simulation of feedback control with time constants of seconds coupled to building energy models with time constants of hours leads to stiff ordinary differential equations. Their efficient numerical solution requires implicit solvers [13].

Non-stiff systems: In EnergyPlus and in many TRNSYS component models, HVAC equipment and controllers are generally approximated using steady-state models, resulting in algebraic equations. Hence, the resulting system model is not stiff as the only dynamics is from the building model. In this situation, explicit time integration algorithms are generally more efficient [14].

Hybrid systems: Hybrid systems require proper simulation of coupled continuous time, discrete time and discrete event dynamics. This in turn requires solution methods with variable time steps and event handling. For example, when a temperature sensor crosses a setpoint or a battery reaches its state of charge, a state event takes place that may switch a controller, necessitating solving for the time instant when the switch happens and reducing accordingly the integration time step. Standard ordinary differential equation solvers require an iteration in time to solve for the time instant of the event, and reinitializing integrators after the event, which both

Please cite this article in press as: M. Wetter, et al., Equation-based languages – A new paradigm for building energy modeling, simulation and optimization, Energy Buildings (2015), http://dx.doi.org/10.1016/j.enbuild.2015.10.017