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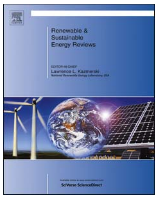

Current software barriers to advanced model-based control design for energy-efficient buildings

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ABSTRACT

Fast and easy advanced model-based control design for energy-efficient multi-zone buildings is crucial for optimal energy savings, and this strongly depends on the availability and capability of advanced simulation and control design software and tools. In this paper, first a state-of-the-art review of the commonly used major software and tools by the community is done with respect to the barriers they present to advanced model-based control design for energy-efficient buildings. Next, the relevant novel concept of Functional Moke-up Interface is reviewed and the associated advances up to date are summarized. Finally, a set desired control-oriented features for new generation tools are given towards better solutions for energy-efficient building control designs.

1. Introduction

Building sector has the largest slice, approximately 40%, in the total end-use energy consumption [1], and around half of the building energy use is for heating, ventilation, and air conditioning (HVAC) [2]. Fig. 1 shows the major components in a building energy system and the flow of energy. As clearly seen in Fig. 1, energy controllers are at a key position in this flowchart network. Intelligent thermal control of buildings plays a key role for reducing building energy consumption through optimal coordination of building HVAC equipments and energy sources (fossil fuel-based sources and renewable energy sources). Among intelligent control methods, model-based approaches are preferred since they are using differential equation-based thermal models of buildings, their heating/cooling energy sources, and their HVAC equipments. These thermal models include thermal interactions between the components and the main dynamics to be controlled [4]. These mathematical models can be used in a mathematical optimization control framework to find the best possible solution. This best possible solution, in turn, means optimal energy savings, minimal greenhouse gas emissions and user thermal discomfort. For example, it was demonstrated in many real-time building control experiments that model-based control approaches can achieve up to 40% energy savings compared to conventional rule-based controllers [5–7].

The next generation buildings are expected to be green buildings, which integrate renewable energy sources (geothermal energy [8–13], solar energy [14,15], wind energy [16,17], etc) as thermal or electrical energy source for their HVAC equipments. Moreover, future smart buildings require demand response management, which is a load management program for buildings to reduce peak energy usages and energy cost [18,19]. When all these desired features are combined, it is clear that optimal building energy management (BEM) is a complex task, and mathematical model-based control solutions provide a significant potential.

The objective of this paper is to review the the current software barriers to advanced model-based control of buildings integrated with sophisticated HVAC equipments and renewable energy systems. Major tools used by the community are analyzed, and the up-to-date solutions to alleviate these barriers are summarized. In the rest of text, when we talk about optimal control of buildings (or equivalently optimal BEM), we mean control of multi-zone buildings integrated with renewable energy sources, new generation HVAC systems (for example, TABS (thermally activated building systems) [20]) and including demand response management.

There exist advanced model-based control design approaches for energy-efficient operation of buildings: for example, nonlinear control, gain-scheduled (GS) control, robust control, networked control, dynamic programming (DP), stochastic model predictive control (SMPC), adaptive model predictive control (AMPC), and hybrid control [21–29]. A short summary of these advanced control methods is given in Table 1, and for more details the reader is referred to [30]. These methods have the potential for providing more energy savings, giving less user thermal discomfort, and some of them can be more robust compared to a rule-based controller or a linear nominal MPC controller, which are the current state-of-the-art controllers in the building sector.

Availability and capability of advanced simulation and control

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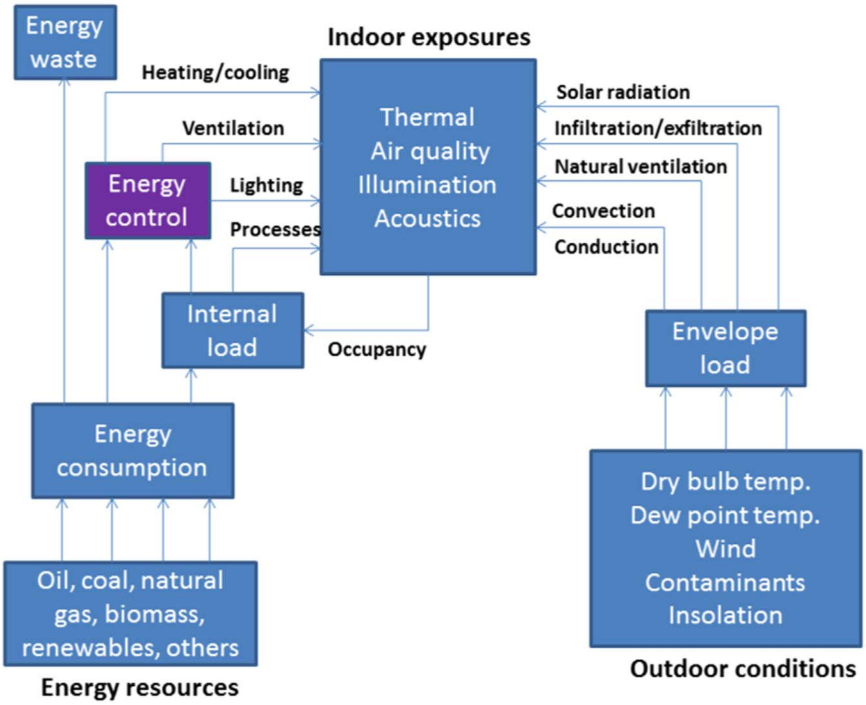

Fig. 1. Energy flow and its control inside a building, a modified version from [3]. The energy controller is shown by the purple box. Advanced model-based energy controllers have significant potential for optimal energy savings.

design software/tools are important for fast and easy advanced model-based optimal control designs. The used software can be categorized as a simulation software, a control design software, or as a multi-task software which can be used both for simulation and control. Control design requires either the real building to test the designed controller or a simulation software to construct a detailed accurate model of the real building (to be called an "emulator model"). Testing a designed controller on a real building may be hard, may not be practical, or it can be costly. As an alternative, controllers are tested on emulator models many times for performance prediction before implementing on the real buildings. *As a result, a simulation software for thermal/energy simulation of buildings, their HVAC equipments, and the integrated heat/cold production units is as equally important as a control design software.*

The current state-of-the art simulation and control software/tools used by the community working on energy-efficient buildings present serious barriers for advanced model-based control. For the analysis of these barriers, the following commonly used major software and tools are discussed: Matlab/Simulink, Modelica/Dymola, TRNSYS, EnergyPlus, Revit, HOT 2000, ESP-r, and IDA-ICEA. The reader is referred to review papers [31–36] for contrasting many other capabilities of a large set of software/tools, to [37] for a review of computer tools for analysing the integration of renewable energy into various energy systems including buildings, and to the website http://www.

Table 1
A short summary of advanced model-based control methods for energy-efficient building operation.

Control Method	A short summary
Nonlinear control	Nonlinear state-space models of buildings or their HVAC, renewable energy systems are used for controller design. It is suitable since building and HVAC thermal models are nonlinear (at least bilinear) in general. It has a potential to give better results compared to a linear control method. However, local optima and convergence issues may arise since the corresponding control optimization problems are almost always non-convex problems
Gain-scheduling (GS)	Building and/or HVAC, renewable energy dynamics are divided into multiple models (in general linear models) based on operating points. For each model, a corresponding controller is designed using the well-established linear control machinery. The controllers are interpolated in real-time implementations. GS allows nonlinear/time-varying models to be used, and it has a potential to outperform a linear control method.
Robust Control	It includes a set of different control approaches (robust MPC, H_∞, etc) to handle uncertainties in building/HVAC/renewable energy thermal models and prediction inputs (for example, solar and internal gains). Although it may give conservative energy savings, it removes the constraint of very accurate system modeling (which may be hard and costly).
Networked control	Large-scale multi-zone building and/or HVAC thermal dynamics are divided into sub-models. Local controllers are designed for each sub-system. The controllers may be totally isolated (decentralized control), they may be coordinated through a higher level controller (hierarchical control), or they may exchange information (distributed control). Given the fact that most of the practical implementations of HVAC equipments and their associated control platforms are physically distributed within the building, networked control may be appropriate for many cases.
Dynamic programming (DP)	Based on the "principle of optimality" in optimal control theory, control inputs are calculated recursively from the end time to the starting time of the control period, and then they are stored in a database. In real-time implementation, controller realization is done using this database, interpolation, and the measured (estimated) state and predictable disturbances of the system. DP is a global optimal and closed-loop control method and can be used for nonlinear models. However, it can be applied only at the zone level in a decentralized way due to the "curse-of-dimensionality" issue.
Stochastic MPC (SMPC)	An MPC method where uncertainty in some input variables (for example, solar and internal gains) is modeled stochastically using their statistical information. SMPC has the potential of handling input uncertainties, and it can be less conservative compared to robust control.
Adaptive MPC (AMPC)	An MPC method where the model used for controller design and controller model are updated online. AMPC has the potential of handling nonlinearities and time-varying characteristics in the system.
Hybrid control	Powers of multiple control methods are combined. Hybrid control can be appropriate in cases a single control approach fail or give poor results.