Energy and Buildings 152 (2017) 73–85

Contents lists available at ScienceDirect

Energy and Buildings

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

PMV-based event-triggered mechanism for building energy management under uncertainties☆

Zhanbo Xu [a,*], Guoqiang Hu [b], Costas J. Spanos [c], Stefano Schiavon [d]

[a] Berkeley Education Alliance for Research in Singapore, 068898, Singapore
[b] School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore
[c] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA
[d] Center for the Built Environment, Department of Architecture, University of California, Berkeley, CA 94720 USA

ARTICLE INFO

Article history:
Received 6 March 2017
Received in revised form 8 June 2017
Accepted 5 July 2017
Available online 14 July 2017

Keywords:
Building energy management
Event-triggered mechanism
Operational optimization
Predicted mean vote (PMV) index
Uncertainties in building operation

ABSTRACT

This paper provides a study of the optimal scheduling of building operation to minimize its energy cost under building operation uncertainties. Opposed to the usual way that describes thermal comfort using a static range of air temperature, the optimization of a tradeoff between energy cost and thermal comfort predicted mean vote (PMV) index is addressed in this paper. In order to integrate the calculation of the PMV index with the optimization procedure, we develop a sufficiently accurate approximation of the original PMV model which is computationally efficient. We develop a model-based periodic event-triggered mechanism (ETM) to handle the uncertainties in the building operation. Upon the triggering of predefined events, the ETM determines whether the optimal strategy should be recalculated. In this way, the communication and computational resources required can be significantly reduced. Numerical results show that the ETM method is robust with respect to the uncertainties in prediction errors and results in a reduction of more than 60% in computation without perceivable degradation in system performance as compared to a typical closed-loop model predictive control.

1. Introduction

Energy consumption worldwide is continuously increasing with the rise in living standards and the global population. Improving energy efficiency for end-users is an effective way to alleviate the energy crisis [1,2]. Building sector accounts for 40% of all primary energy consumption and more than 70% of electricity consumption [3]. One salient feature of the building operation is that its demand profiles are flexible due to the building thermal storage process and the elastic requirements of occupants. This flexibility provides a huge potential for building energy efficiency. Therefore, the optimization of building operation is becoming a necessity which has attracted more attention in recent years. With the sustaining development of smart microgrid technologies, many efforts have been made to optimize the building operation while satisfying the requirements of occupants. A basic optimization method is to develop building models that capture the system dynamics and requirements of occupants, and proceed to find the optimal solution based on these models.

Generally, there are three ways to develop a building performance/energy model that incorporates mechanical systems (heating, ventilation, and air conditioning – HVAC). First, one can develop a physics-based model using simulation software such as EnergyPlus [4] and TRNSYS [5]. A precise model is obtained this way, but it is time consuming and expensive to develop and requires immense computational resources. Second, the model can be developed using machine learning methods such as artificial neural networks [6] and regression models [7]. Although developing the model in this way is relatively easy and requires less computational resources, a lot of training data is required to produce a model with high prediction accuracies. Third, the model can be developed using simplified physics principles-based state equations of building thermal dynamics such as the models developed in [8–10]. This type of the models is simpler than simulation-based models, but it can address tradeoffs between accuracy and com-

☆ This work was supported by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore.

* Corresponding author.
E-mail addresses: zhanbo.xu@bears-berkeley.sg (Z. Xu), gqhu@ntu.edu.sg (G. Hu), spanos@berkeley.edu (C.J. Spanos), stefanoschiavon@berkeley.edu (S. Schiavon).

http://dx.doi.org/10.1016/j.enbuild.2017.07.008
0378-7788/

putational resources. In general, the last two types of the modeling methods are usually used for various optimization and control purposes. For example, based on the second type of the methods, an optimization problem was developed in [6] to capture a tradeoff between energy saving and thermal comfort level, a multi-objective optimization of energy consumption and thermal comfort was formulated in [7], and optimal control problems for HVAC system were developed in [10,24] respectively. Based on the third type of the methods, an optimization problem of a tradeoff between energy saving and air quality was developed in [8], an optimal scheduling problem for energy devices in smart homes was formulated in [9], and an joint control problem of active and passive heating, cooling, lighting, shading, and ventilation in buildings was addressed in [25].

Based on the models mentioned above, many optimization methods have been developed to facilitate building energy efficiency. For example, mixed integer programming is such a conventional method, since the problem always contains both continuous and discrete variables [9,11]. Model predictive control (MPC) is another method usually used to address the problem under uncertainties. Existing results obtained in [10,12,13] showed that MPC features high energy and cost saving since the future evolution of system dynamics is involved in the decision-making process and the optimal solution is obtained based on a rolling horizon basis. Kwadzogah et al. [13] provided a review of MPC for HVAC systems. Event-based optimization methods have recently been applied to building energy efficiency such as in [14,15]. This type of the methods is computationally efficient for solving large-scale problems since their state space can be significantly reduced by the events defined by a set of state transitions. In addition, many other methods, such as genetic algorithms [7,18], fuzzy control [16,17], simulation-based optimization methods [4,5], etc., were attempted. The above literature showed that 10%–30% of energy consumption (costs) can be reduced by the optimization of building operation.

However, building operational optimization still faces many challenges, two of which that are very relevant are a high level of thermal discomfort and uncertainties in building operations. Regardless of the high energy consumption, a majority of occupants are still not satisfied with their thermal environment [19]. Therefore, an elaborate model for describing occupants' thermal comfort should be involved in the optimization of the building operation. Since the thermal comfort of occupants is mainly determined by the indoor air temperature, mean radiant temperature, humidity, air velocity, metabolic activity and clothing insulation, the selected model needs to reflect the influence of the above factors on thermal comfort, such as in the well-known predicted mean vote (PMV) model [20]. However, it may be computationally expensive to directly integrate the PMV model with the optimization procedure due to its non-convex and nonlinear properties. Building demand profiles feature impactful uncertainties due to random weather conditions and occupants behaviors. Both of these uncertainties have a significant impact on the building energy efficiency and thus need to be addressed. Many methods have been proposed to handle these uncertainties, but most of them, such as MPC and rolling horizon methods, are time-triggered. Through the time-triggered methods, the optimal solution is recalculated once at each sampling stage. However, the recalculation at stages when the building system is operating within a desirable range is clearly a waste of communication and computational resources, which may make the broad deployment of such methods unnecessarily costly, especially for large-scale building systems.

A typical control system for the building operation includes two levels. The goal of the upper level is to obtain an optimal scheduling strategy of the energy devices to minimize energy cost or consumption while satisfying the thermal requirements of occupants. The goal of the lower level is to adjust the local actuators to track the scheduling strategy obtained from the upper level. In this paper, we focus on the scheduling problem of the building operation in the upper level. Through addressing the challenges mentioned before, we make the following contributions. First, an optimal scheduling problem of the building operation is developed based on a steady state model for building energy dynamics to capture a tradeoff between the energy cost and the PMV index. In this problem, we develop a piecewise linearization-based approximation of the original PMV model to predict the thermal comfort of occupants. This approximate PMV model does not introduce significant errors but is computationally efficient for the optimization purpose. It is also found that compared to the usual way that describes the thermal comfort by a static range of indoor air temperature, the proposed model provides more flexibility and hence exhibits more potential on both energy cost savings and demand reduction. Second, we develop a model-based periodic event-triggered mechanism (ETM) to handle the uncertainties in the building operation especially those in the outdoor temperature, solar radiation, usage pattern of electrical appliances, and occupancy. Upon triggering of two events defined by the state transitions of the occupancy and thermal comfort of occupants, the ETM determines whether the optimal strategy should be recalculated at each stage. In this way, the communication and computational resources can be significantly reduced. Third, the performance of the ETM method is tested based on an office-room environment in Singapore. Numerical results show that the ETM method is robust with respect to uncertainties in prediction error, and it can reduce the communication and computational resources by more than 60% without perceivable degradation in the system performance as compared to a typical closed-loop MPC method.

The rest of the paper is organized as follows. The problem formulation is presented in Section 2. The approximate PMV model and the ETM method are developed in Section 3. In Section 4, the performances of the approximate PMV model and the ETM method are evaluated and validated using case studies of an experiment in Singapore. The discussion for the proposed work and the conclusions are given in Sections 5 and 6 respectively.

2. Problem formulation

A daily scheduling problem of the building operation based on a discrete-time formulation is presented in this section. The scheduling horizon, i.e., 24 h, is discretized into K stages. The objective is to minimize the building electricity cost in response to a time-of-use (TOU) electricity price over the scheduling horizon, while satisfying the thermal comfort of occupants. This problem formulation is developed based on an office-room environment in Singapore. In the following, the models for the thermal comfort of occupants and the room energy dynamics are presented in Sections 2.1 and 2.2 respectively. The objective function is shown in Section 2.3.

2.1. Model for thermal comfort of occupants

In most of the existing studies on the optimization of building operation, the thermal comfort of occupants is usually described by a static range of indoor air temperature, since it would not provide any computational challenges to solving the optimization problem. However, describing the thermal comfort by a static range of indoor air temperature is conservative and inadequate since it is determined by six main variables of environmental factors (which are the indoor air temperature, mean radiant temperature, relative humidity, and air velocity) and personal factors (which are the clothing and metabolic rate of the occupant). We select the well-known PMV model in this paper to elaborately describe the thermal comfort of