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Event-driven optimization of complex HVAC systems

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ABSTRACT

Real-time optimization (RTO) has been developed to improve the cost and/or energy efficiency of complex heating, ventilation and air-conditioning (HVAC) systems. In current literature, almost all of the developed real-time optimization methods belong to the type of time-driven optimization, in which the action of optimization is triggered by “time”. As optimization should be done when the system operating conditions experience a change that is large enough to cause current operational setting not optimal any more, optimization strategies should recognize ‘significant’ changes and perform optimization when necessary. Since the time-driven optimization is a periodic mechanism in nature while those ‘significant’ changes may not be periodic, the time-driven optimization cannot capture ‘significant’ changes and do the optimization promptly. Therefore, this paper proposes an event-driven optimization (EDO) for complex HVAC systems, the key idea of which is to use “event” rather than “time” to trigger the action of optimization. A systematic event-driven optimization method is illustrated, where its main tasks, including event definition and event identification, will be discussed. The proposed method will be compared with a conventional time-driven method using case studies, through which the main advantages of the proposed method will be identified.

1. Introduction

Heating, ventilation and air-conditioning (HVAC) systems contribute the significant part (20–50%) of building energy consumption [1]. It is worthwhile to consider real-time optimization (RTO) in HVAC systems since large energy savings could be obtained from a small improvement in operating efficiency [2]. Real-time optimization is a type of optimization that optimizes control settings or variables (or decision variables) to minimize or maximize a predefined cost function [3]. It has been used in HVAC systems since the 1980s [4]. In the 1990s, most studies focused on the real-time optimization of the local loops or subsystems of HVAC systems using classic linear/quadratic programming, or gradient-based iterative methods [5,6]. Recently, to address the complexity of large-scale HVAC systems, advanced optimization algorithms have been developed, such as evolutionary algorithms [7], branch and bound [8], simulated annealing [9], and so on. ASHRAE handbook surveyed the publications since 1980s [10]; and new developments till 2008 were reviewed by Wang and Ma [11].

In the real-time optimization of HVAC systems, the majority of the developed methods belong to the type of time-driven methods, in which the actions of optimization are triggered by “time” periodically whether using a fixed optimization frequency or a scheduled timetable, *i.e.* the optimization will be done at predefined time instants according to current available information. For example, Kusiak et al. [12] investigated the real-time optimization of air handling unit (AHU), in which the supply air pressure and temperature were optimized every hour. They showed that 7.66% of the total energy consumption can be reduced. Mossolly et al. [13] tested the hourly optimization of the fresh air flow rate and the supply air temperature in a VAV system and demonstrated that 30.4% of the energy consumption can be reduced over the summer season (4 months). Yoon et al. [14] developed a real-time optimization strategy for a double-skin façade system, in which the blind slat angel, airflow regime and opening ratio were optimized every 15 min to achieve the minimal energy consumption. In the work of Zaheeruddin and Zheng [15], 24-h operation was divided into three modes based on time: night set-back mode (5:00 P.M.–7:00 A.M.), start-up mode (7:00 A.M.–8:00 A.M.), and normal mode (8:00 A.M.–5:00 P.M.). The optimization actions were only performed when the operation mode was changed.

In a time-driven method, a suitable optimization frequency is important for the performance of optimization [16]. Basically, a

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higher frequency will lead to a better performance because the response to the variation of operating conditions is faster [17]. However, it is known that optimization should be done when system operating conditions experience a significant change that causes current operational settings not optimal any more [10]. Therefore, an optimization strategy should recognize ‘significant’ changes and performance the optimization accordingly only when necessary. As the time-driven optimization is a periodic mechanism in nature while those ‘significant’ changes may not be periodic (actually they are stochastic and difficult to predict), the time-driven optimization may not capture ‘significant’ changes and do the optimization promptly. Although one can choose an extremely high optimization frequency such that the random change can be captured with minor delay, a higher frequency will increase the computation burden, which will be critical when the system computational resource is limited, especially for a large-scale system where a number of decision variables are taken into account [18,19]. Besides, a higher frequency may waste the computational resource when operating conditions are stable and optimization is not necessary (but still be performed) [20,21]. Therefore, a new control optimization mechanism is needed, which should recognize ‘significant’ changes and perform the optimization only when necessary.

In this paper, an event-driven optimization (EDO) method is proposed. The key idea of the event-driven optimization is to use “event” rather than “time” to trigger the action of optimization. It should be noted that the event-driven method (also known as “event-based” or “event-triggered”) is not a new concept. It originates from the study of discrete event systems [22]. A nice feature of the event-driven paradigm is that it is able to follow the stochastic behavior of system operation, and thus increasing the flexibility of control, communication and optimization [23]. Previous studies have already shown that event-driven mechanism can reduce the computation load effectively while simultaneously ensure the control or optimization performance. For example, without sacrificing the performance, 50% reduction of computation load was achieved in [24] and 70–80% of computation reduction was achieved in [25]. These studies have demonstrated the potential of event-driven control.

It is noticed that until now there is very few studies on this specific topic on the feasibility of applying event-driven optimization to HVAC systems. As the operation of HVAC systems usually confronts many stochastic and unpredicted ‘state transmission’, such as weather condition changes, load changes and occupancy changes, “time” may not be a good driver for the real-time optimization. Given the potential of event-driven optimization, this paper develops a framework of event-driven optimization for HVAC applications and evaluates its performance by comparing with the conventional time-driven optimization. Firstly, the event-driven optimization is illustrated in a systematic way, where its main tasks, including event definition and event identification, are discussed. Then, case studies are conducted to demonstrate the application potential of the event-driven optimization in HVAC systems. The performances of the event-driven and time-driven optimization are compared, based on which the main advantages of the proposed method will be discussed.

2. Event-driven optimization

2.1. Basic framework

The framework of the event-driven optimization is illustrated in Fig. 1. The event space is a collection of events that will be used to trigger the action of optimization, which should be defined before the implementation. The occurrence of an event is identified through analyzing real-time operational data or monitoring data. If an event is identified, control optimization will be executed to find optimal values of decision variables with respect to concerned objectives. Otherwise, no action will be taken. Note that optimization algorithms that are developed for time-driven method can also be used to optimize decision variables in this framework.

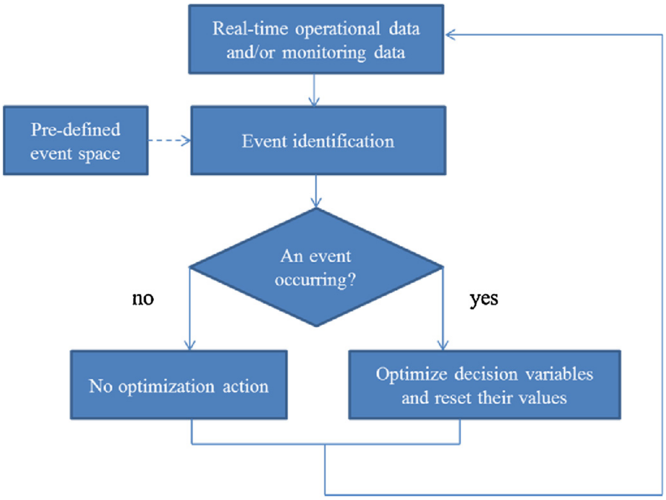

Fig. 1. The framework of event-driven optimization.

2.2. Event definition

To achieve the real-time optimization in an event-driven manner, defining events is vital since it decides when to take the action and will significantly affect the system performance. Basically, an “event” should be defined as something physically happening which can reflect the system state transition [22]. For example, a chiller being switched on can be considered as an ‘event’; and the cooling load increased by 10% can be considered as an event as well. Hence, ‘event’ can be defined naturally from a digital state (e.g. the status on/off of chiller), or a continuous state (e.g. the cooling load):

$$e:=\begin{cases}\eta\left(x_{t_0}\to x_{t_1}\right)>\sigma_e & \text{for continuous state transition}\\ \eta_{t_1}\neq\eta_{t_0} & \text{for digital state transition}\end{cases}\qquad(1)$$

where η is the state corresponding to the event; x is a set of variables that can be used to reflect the event state; σ_e is a predefined threshold; t_1 indicates the current decision time; and t_0 indicates the last decision time.

In daily operation of a complex HVAC system, events may come from environment (such as weather changes and solar radiation changes), system itself (such as equipment on/off, equipment faults and operation mode changes) and occupants (such as occupancy changes and occupants’ adjustment of thermal comfort related variables), which can be regarded as different sources of events. As not all of ‘state transition’ should be used as ‘events’ to trigger optimization, only those ‘state transitions’ which could cause a significant influence on concerned objectives (such as energy efficiency) will be defined as events. The collection of all the events forms an event space as below:

$$E_{space}:=\left\{e_{1,}\cdots,e_N\right\}\qquad(2)$$

Prior knowledge, computer simulation and/or operational data analysis (e.g., data mining) should be resorted to find the importance of ‘state transition’ with respect to concerned optimization objectives (such as energy use). It should be noted that for events with continuous states, thresholds are necessary for the definition. A suitable threshold may depend on the particular system that is