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Energy trade off analysis of optimized daily temperature setpoints

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ABSTRACT

We introduce a systematic approach for analyzing the energy consumption of four control policies (i.e., zone level daily optimal control, zone level annual optimal control, building level daily optimal control, building level annual optimal control), which differed based on their temporal and spatial control scales. In order to integrate occupant thermal comfort requirements, we defined uniformly distributed random constraint functions on the setpoints. We used the DOE reference small office building in three U.S. climate zones for simulating the performances of control policies, using EnergyPlus. Among the four control policies, the building level annual control policy showed close to the highest energy efficiency (27.76–50.91% (average of 39.81%) savings depending on the climate) with comparatively small training data requirements. In addition, the building level daily optimal setpoint selection, subject to thermal comfort constraints, leads to 17.64–38.37% (average of 26.61%) energy savings depending on the climate. We also demonstrate that temporal scale of the policies have a statistically significant impact on the small office building's energy consumption while spatial scale's impact is insignificant.

1. Introduction

Commercial and residential buildings account for approximately 30% of the total energy consumption in the world and contribute substantially to the climate change, i.e., 30% of the global greenhouse gas emissions [1]. This share is larger (about 40% of the total energy consumption [2]) in the developed countries. The growth in the population, the increasing demand for better building services and improved comfort, in addition to the rise in the time spent in buildings, result in an ever increasing building energy consumption [3]. HVAC systems, which are responsible for providing comfortable thermal conditions and acceptable air quality in buildings, account for the largest share in energy usage and gas emissions (about 50% of the consumption in the developed countries [3]).

Majority of the HVAC system controllers work with a negative feedback control loop based on indoor air temperature [4,5]. In this control logic, the error between a target state (i.e., a temperature setpoint) and the feedback (i.e., a thermostat reading) should not exceed a threshold (i.e., deadband). HVAC systems often use fixed control parameters in compliance with the standards (e.g., ASHRAE Standard 55 [6], ASHRAE Standard 62.1 [7]), which assume thermal comfort is static over time. However, it has been shown that dynamic environmental variables (e.g., outside temperature [8]) and user related variables (e.g., physical acclimation [9]) influence thermal comfort, making it dynamic over time [10–13]. For example, occupants prefer higher setpoints in the summer compared to the winter [11], and buildings also consume less energy at higher setpoints in the summer compared to the winter. Therefore, smart selection of higher setpoints in the summer and lower setpoints in the winter provide an opportunity to not only conserve energy, but also improve thermal comfort. However, it is important to note that the highest or lowest setpoints are not always the most energy efficient setpoints [14,15].

In a previous study, we demonstrated that a control policy that selects optimal setpoints on a daily basis with a fixed spatial scale (i.e., one setpoint for the entire building) considerably reduces the energy consumption compared to a control policy that selects an optimal setpoint on an annual scale [14]. The savings ranged from 6.78% to 37.03% depending on the climate and building size with an average of 16.4%. However, consideration of the impact of other factors on HVAC performance, such as the internal heat exchange between the zones, might provide opportunities to optimally select zone level optimal control parameters to improve the energy efficiency at the building level. Therefore, a control policy that optimizes the HVAC performance on a daily basis at the zone level could potentially improve the overall

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building energy efficiency. In addition, imposing thermal comfort constraints on the selection of the optimal control parameter selection impacts the effectiveness of the control policies. Understanding the impacts of spatial (i.e., building level and zone level) and temporal (i.e., annual and daily) scales of the controllers on the overall HVAC system energy consumption under thermal comfort constraints is the primary gap explored in this paper.

Thus, we introduce a systematic approach for analyzing four control policies, which differ based on their temporal and spatial scales: (1) building level annual optimal control policy, (2) zone level annual optimal control policy, (3) building level daily optimal control policy (introduced and validated in a previous study [14]), and (4) zone level daily optimal control policy. The first and the third control policies assign optimal control parameters at the building level, while the second and fourth operate at the zone level. Therefore, the focus of this study is to compare optimization of a single value for a cluster of setpoints with multiple values for setpoints. The first and second control policies select optimal parameters on an annual basis, while the third and fourth policies select optimal parameters on a daily basis. In order to represent the impact of personal comfort on these control policies, we used a uniformly distributed noise generating function to simulate occupants comfort and constraint the optimal control parameters and compared the energy consumption of these control policies with each other. We used the small size office building reference simulation model developed by the Department of Energy (DOE) [16] for comparing the four control policies in three United States climate zones.

The paper is organized as follows. A review of the recent studies on optimal controllers and control policies for comfort driven HVAC operations is presented in Section 2. We explain the design and implementation of the four control policies, discretization of the simulation factors, and data analysis in Section 3. We present the energy simulation models and procedures in Section 4. Section 5 provides the results of the comparison of the four control policies. Limitations on the generalization of the findings and future steps of the research are presented in Section 6. Finally, Section 7 provides a summary of the results and conclusions of the paper.

2. Literature review

An HVAC thermal zone level controller operates based on two control parameters defined as a setpoint (target value) and deadband (performance relaxation range around the setpoint). The higher value on the deadband is referred to as the cooling setpoint and the lower value on the deadband is referred to as the heating setpoint. Extending both heating and cooling setpoints increases the deadband. Since it is well known that maximizing the deadband always results in energy efficiency because it increases the no-operation margin around the setpoint, this paper focuses on the smart selection of setpoints rather than the impact of increasing the deadband.

Control policies for optimizing HVAC setpoints can be divided into two categories: (1) control policies that are complementary to the existing HVAC control logic and that influence the performance of HVAC systems by solely adjusting the indoor air temperature setpoints [14,17,18], and (2) operational policies that intervene existing HVAC control logics (e.g., order, condition, and loop) and that require the dynamic control of local subsystems [19]. In this paper, we focus on the techniques in the first category due to the fact that these techniques could be easily generalized, they work for any type of HVAC system and do not require a model of an HVAC system (making them model free). However, optimizing the operation of HVAC systems solely for setpoints might result in thermally uncomfortable conditions for building occupants. For example, an occupant might prefer a cool environment while the optimal control parameters result in a much warmer thermal environment than the desired level. Therefore, we also narrowed down our review to the techniques that allow for integration of dynamic personal thermal comfort requirements into HVAC control loop.

Researchers have proposed various personalized and real-time comfort sensing approaches, which can potentially be used in existing buildings. A model predictive control (MPC) optimization environment, introduced in [20], couples the environment to a building automation system, allowing real-time optimization, considering operator overrides and updated weather forecasts to predict optimal building control strategies. Through determining hourly HVAC cooling setpoints and supply water temperature for minimizing the daily energy cost, 5–54% energy savings and improvement in occupants' comfort were achieved. The setpoints were fixed across the building systems and only varied over time (i.e., temporal scale). Authors of [17] developed a multi-objective genetic algorithm for optimizing a building's mechanical systems performance. The optimization algorithm operates complementary to a building's central control system. The optimization process strives to maximize energy efficiency and thermal comfort by searching the supervisory control strategy setpoints, such as supply air temperature, supply duct static pressure, chilled water supply temperature, minimum outdoor ventilation, reheat (or zone supply air temperature). HVAC system steady-state models, developed and validated against the monitored data of the existing VAV system, were used for energy use and thermal comfort calculations. Comparing actual and optimal energy use, the authors demonstrated that the proposed control strategy could save energy by 16% for two summer months while satisfying minimum zone airflow rates and zone thermal comfort. It was then concluded that the proposed control strategy with required constraints could improve the operating performance of the existing HVAC system. Similar to the previous study, the setpoints were uniform across building for each subsystem and it solely varied over time (i.e., temporal scale). A methodology for optimizing building supervisory control in simulation has been introduced in [21]. Their stochastic model predictive control (SMPC) architecture is capable of incorporating different levels of variability in building performance due to occupant behavior and provided control setpoints which lead to more conservative building performance. A set of time windows enabled the use of complex building models in energy simulations. The case study results showed that stochastic optimization led to a more conservative and more reliable 33% performance improvement compared to the 50% performance improvement of deterministic optimization. Similar to two previous studies, the setpoints were uniform across the building for each subsystem and it solely varied over time (i.e., temporal scale). Authors in [22], applied computational intelligence algorithms to solve the non-parametric model for minimization of HVAC energy consumption and room temperature ramp rate Through real-world implementation of the methods, their results indicated that particle swarm optimization and harmony search algorithms are suitable for solving the proposed optimization model. The computational results demonstrated that energy savings could be achieved by optimizing the settings for the supply air static pressure set point and discharged air temperature set point on a temporal scale. Authors in [23] applied a novel control method using multi-dimensional interpolation between optimized control configurations for various steady-state load distributions on a system with arbitrary steady-state and transient load distributions. Applying the method on a two-room HVAC system predicts power savings for an arbitrary steady load that is nearly equivalent to that using a Variable-Air-Volume air condition system with chiller modulation. However, the new method provides 19% energy savings over an uncontrolled system compared to energy savings of 6% for a VAV with chiller modulation for arbitrary transient loads. This method applied the control strategy mainly on a spatial scale and did not consider the implications of temporal scale.

Although extensive research has been conducted to improve HVAC system energy efficiency through customizing the control of setpoints based on comfort requirements, all of the above mentioned studies have focused either on the temporal control scale or on the spatial control scale– not on both temporal and spatial control scales simultaneously [24]. Understanding the impacts of both temporal and spatial scales in

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