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Occupant-oriented mixed-mode EnergyPlus predictive control simulation

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A B S T R A C T

Model predictive control (MPC) has been studied in the building science realm for about three decades. However, the following two aspects of the building control have not been studied thoroughly in MPC research. One is the impact of the mixed-mode cooling system on the active heating ventilation and air conditioning (HVAC) energy consumption, and the other is the differences of individual thermal comfort preference and its impact on energy. This paper proposes an occupant-oriented mixed-mode EnergyPlus predictive control system to optimize HVAC energy consumption while meeting the individual thermal comfort preference. A web-based dashboard is implemented in the test-bed building for three months to collect individual thermal comfort preference data. The data analysis results suggest that occupants have various tolerances and preferences about thermal comfort. The simulation results show that, during one week of a typical swing season, the mixed-mode system further reduces the active HVAC energy consumption, and the diversified occupant thermal comfort preference has significant impact on HVAC energy consumption.

1. Introduction

Building energy efficiency has been improved greatly for the past decades, thanks to the adoptions of new technologies and more stringent building codes and standards. These energy efficiency measures mostly happen during the design, construction and retrofit phases, which are critical yet very short periods of the entire building life cycle. More light should be shed on building controls during the operation stage, which has much longer time spent and stronger impact on energy. On the one hand, without proper control and management, a building that is designed with advanced energy-efficient technology may still consume tons of energy. On the other hand, from the facility managers' standpoint, to ensure occupant comfort (without complaints) is often the prioritized responsibility. A building control system is the means to deliver this commitment. Therefore, for both energy efficiency and occupant comfort purposes, building control is the key for the daily building operation in commercial buildings.

To achieve the goal of reducing energy and improve occupant comfort in commercial buildings, model predictive control (MPC) has been investigated for the past three decades. Generally, MPC algorithms allow current control inputs to be optimized in real-time control operations with certain constraints while anticipating future events using mathematical models. Heating, ventilation, and air conditioning (HVAC) systems can usually take advantage of this algorithm to optimize its energy consumption with the constraints of occupant thermal comfort among others. Numerous studies have established simulation and experimental results to demonstrate MPC's effectiveness in reducing energy and ensuring thermal comfort, such as [1–10].

Most of MPC studies focus on active HVAC systems, such as variable air volume (VAV) and radiant heating systems. Mixed-mode passive/active HVAC systems that incorporate window opening strategies may have a greater energy saving potential during cooling and swing seasons in some climates. A few researchers have applied MPC algorithms to mixed-mode HVAC systems. May-Ostendorp et al. developed an MPC control system that can optimize window opening schedules for a mixed-mode HVAC system to reduce energy consumption [11]. On the basis of this offline optimization framework, Corbin et al. developed a real-time optimization framework for the MPC system by linking EnergyPlus, Matlab and a building automation system (BAS). The test cases reported that the MPC system resulted in "54% energy savings with often improved occupant comfort" [12].

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Although most of MPC studies on HVAC systems have addressed thermal comfort, air temperature is often used as the only indicator or constraint. Air temperature is indeed a very influential factor, but is not the only factor that could influence human thermal comfort. Predicted mean vote (PMV) which can be calculated by six major human thermal comfort influencers – air temperature, relative humidity, mean radiant temperature, air speed, metabolic rate, and clothing insulation factors, may better represent occupant thermal comfort as suggested in the following studies [5,13–15].

One difference between using PMV and using air temperature as the thermal comfort indicator is that PMV is able to take into consideration of individual thermal preferences. Several studies have indicated that occupants do not have uniformed thermal sensation in the same thermally controlled space [16,17]. In order to meet the thermal comfort requirements of different occupants, several studies have developed individual thermal comfort voting systems to feedback the subjective thermal preference information into HVAC control systems [14,15,17,18]. For example, Choi [19] developed a wearable control system that can collect thermal measurement data from individual bio-sensors to automatically adjust HVAC system setpoints. The experiment and simulation results of these previous studies show that providing occupants with individual thermal controls not only can improve occupant satisfaction [15,19] and comfort [14,17–19], but also impact the HVAC energy consumption [14,15,17–19].

This study develops four control schemes using a test-bed office building to optimize its energy performance while maintaining the occupant thermal comfort. In Section 2, a systematic method of creating four control models is presented. First, a baseline rule-based control model is created to demonstrate a co-simulation platform and establish a baseline energy and thermal comfort performance. Second, an EnergyPlus predictive control (E+PC) system is developed to reduce the active HVAC energy consumption while maintaining the average occupant thermal comfort. Then, on the basis of E+PC, a mixed-mode EnergyPlus predictive control (ME+PC) is modeled to further reduce the test-bed building's energy consumption by incorporating passive cooling strategies in the active MPC system. At last, in order to meet individual thermal comfort requirements, a subjective feedback data collection dashboard is designed and experimented in the test-bed building for three month. Based on the data analysis results, an occupant-oriented mixed-mode EnergyPlus predictive control (OME+PC) model is developed and simulated. In Section 3, the simulation results as well as the data analysis results of the occupant subjective thermal comfort experiment are presented and discussed. The conclusions are made at the end of this study.

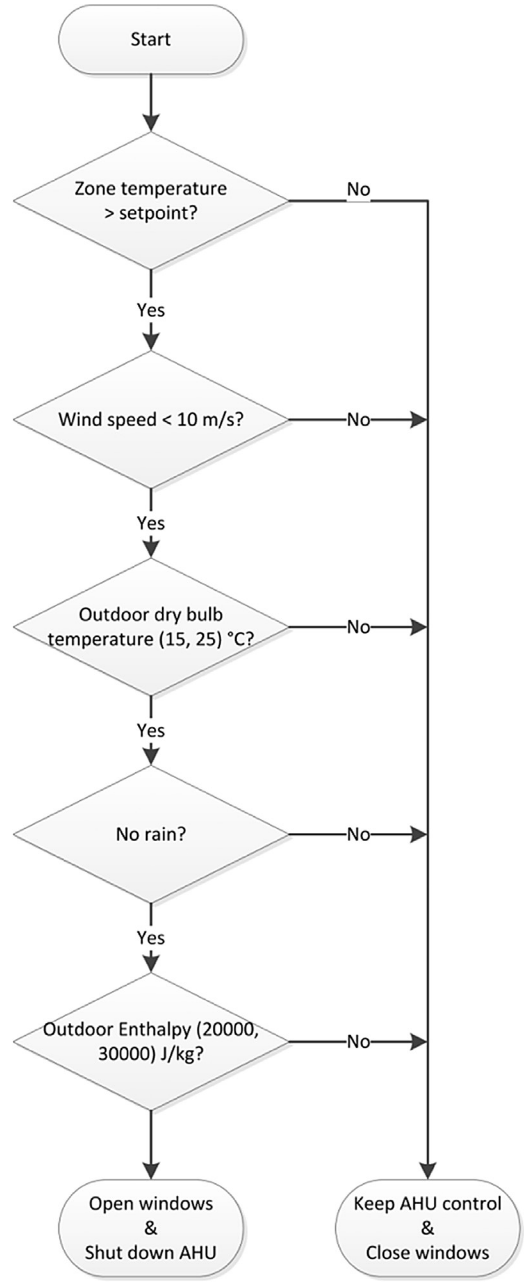

Fig. 1. Window opening control logic.

2. Methodology

2.1. Case study overview

A 2-story, 2262 m^2 office building (Phipps Center for Sustainable Landscapes (CSL) located in the suburban area of Pittsburgh, Pennsylvania, USA) is chosen as a test-bed building to conduct the simulation and experiment.

A baseline control system is developed to establish a co-simulation framework using Matlab/Simulink and EnergyPlus. The baseline energy and thermal comfort performance using rule-based algorithm is simulated as a benchmark for the MPC algorithms. On the basis of this baseline model, an EnergyPlus Predictive Control (E+PC) model is developed. The objective of E+PC is to maintain the same PMV comfort criteria as the baseline control but to minimize the active HVAC power consumption by optimizing the air handling unit (AHU) supply air temperature. Detailed development and implementation schemes of the baseline and E+PC have been captured in a previous study at [20].

2.2. Mixed-mode EnergyPlus predictive control (ME+PC)

On the basis of E+PC, a mixed-mode EnergyPlus Predictive Control (ME+PC) model is developed. The objective of ME+PC is to incorporate the passive cooling strategy into E+PC, so that the control system can handle both active HVAC system and passive motorized window opening system to further reduce the HVAC energy consumption with the constraint of occupant thermal comfort. The motorized window opening control logic is shown in Fig. 1. The logic is selected based on the actual BAS settings at the test-bed building and adjusted for the module of "AvailabilityManager:HybridVentilation" in EnergyPlus, see details at [21].

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