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The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use

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ABSTRACT

Buildings account for nearly 38% of the total energy use in the U.S., and 46% of this use is associated with commercial buildings. More than 40% of the energy in commercial buildings is consumed by HVAC systems, which provide heating, cooling and ventilation to individual zones to maintain comfortable and healthy indoor environments. A more refined control strategy based on actual occupancy might improve HVAC system related energy efficiency. Accurate occupancy profiles are important to determine actual energy demands and corresponding control schedules. This paper focuses on energy efficiency in office buildings with centrally controlled VAV systems by setting zone-level HVAC start/stop schedules using personalized occupancy profiles, which represent occupants' long-term presence patterns. Evaluation of the method was performed using a simulation model, calibrated by the actual energy use data of an office test bed building. Up to 9% of the energy was saved when personalized occupancy profile based HVAC schedules were used. However, if occupants of a zone have different occupancy patterns, the aggregated patterns may hinder any potential efficiency that might be realized from zone-level HVAC start/stop schedules. This paper also presents an approach for reassigning rooms to unify the start/stop times at the zone level by placing occupants with similar profiles in the same mechanical zones. When room reassignment was implemented and coupled with profile based control schedule, HVAC energy use was reduced by another 8%. The proposed methods could provide reliable personalized HVAC control for small-size office buildings without advanced building automation systems, nevertheless, they could also be extended to buildings with packaged HVAC systems and individual air-conditioning systems.

1. Introduction

Buildings account for nearly 38% of the total energy use in the U.S. [1], and 46% of the primary energy use is associated with commercial buildings [2]. In buildings, energy is mainly used to maintain indoor environments and provide building-based services. In the U.S. commercial building sector, HVAC (Heating, Ventilation, and Air Conditioning) systems account for over 40% of energy use [2]. Approximately 34% of the office spaces are equipped with central HVAC systems [3,4] that generate cooling using chillers for heat rejection and distribute it to air-handling units (AHUs) or fan-coil units (FCUs), and generate heating using boilers and distribute it to fan-coil units, radiators, or baseboard heaters [5–7]. It is estimated that 90% of central HVAC systems are operated inefficiently [8]. Instead of basing HVAC schedules on actual building use, most of these systems operate under the assumption that buildings are occupied for a fixed period of time during a day, for example, from 8:00 to 21:00. Often, this assumption deviates considerably from actual building occupancy. Prior research confirms that rooms of a building are often vacant during part of the day or only used occasionally [9–11]. Deviations from the designed occupancy can result in HVAC systems to operate on inefficient schedules. Energy use can potentially be saved if HVAC systems are operated based on actual demands, and occupancy is a key factor in determining those demands. Specifically, two aspects are important: (1) heat gain generated from occupants and the equipment/appliances in use, and (2) occupant comfort. Both of these factors are related to the presence of occupants. Thus, realistic occupancy profiles are essential for setting efficient HVAC schedules in individual spaces. In the context of this paper, *occupancy* is defined as time sequenced occupancy status changes, such as arrival time, duration of stay, and departure time. A *personalized occupancy profile* is one-typical weekday occupancy

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probability as a function of time. An occupancy profile is for a specific occupant, representing the occupant's long-term habitual presence patterns (occupancy patterns).

This paper focuses on energy efficiency in office buildings with centrally controlled HVAC systems, which are divided into three categories: central VAV (variable air volume) systems, central CAV (constant air volume) systems, and central FCU (fan coil unit) systems. Based on the conditioned floor space in office buildings, central VAV systems (23.5%) constitute 58.8% of centrally controlled HVAC systems, thus, central VAV systems are the focus in this paper to improve energy efficiency. With central VAV systems, the whole building is controlled by air handling units, which distribute heating, cooling and ventilation into zones [12,13]. Mechanical zones are the basic thermal control units in an HVAC system; zoning segments the building into particular areas where thermal and ventilation can be individually controlled and adjusted by VAV systems [14]. A VAV could supply air with constant temperature and meet changing loads by varying supply airflow rates [12,15]. A mechanical zone may consist of one room or several rooms. If occupants in a zone have different occupancy patterns, an HVAC start/stop schedule based on their combined occupancy patterns may not accurately represent how each room is actually utilized. Reassigning occupants, who have similar occupancy profiles, to the same zones might unify zone-level HVAC start/stop time and increase energy efficiency. In addition, a VAV system's operation is triggered as a response to zone thermal load changes, therefore, placing occupants with similar profiles may reduce the actual HVAC load and VAV run time, and potentially save more energy. This paper aims to improve HVAC energy efficiency by (1) determining zone-level HVAC start/stop schedules based on occupants' personalized profiles, and (2) reassigning occupants with similar profiles to the same zones. Data gathered from a building energy simulation was used to evaluate the validity of the proposed methods and to measure potential energy savings.

The paper is structured as follows: Section 2 outlines the motivation for the study. Section 3 provides a review on prior research and explained the importance of basing HVAC start/stop schedules on occupancy profiles. Section 4 describes the test bed building used in this study as well as the data preparation process. Section 5 introduces the study objectives and methods used for occupancy profiling, profile clustering, room reassignment, and energy simulation. Section 6 discusses the findings for occupancy profile based HVAC start/stop schedules and room reassignment. Section 7 compares energy use of different scenarios. Section 8 summarizes the limitations of the work and describes potential areas for future research. Finally, section 9 concludes the paper.

2. Study motivation

During the design phase of a building, engineers design HVAC schedules that account for maximum possible occupancy [16]. HVAC systems do not operate efficiently if a building's actual occupancy patterns deviate substantially from the design assumptions. A frequently used HVAC schedule is the one recommended by the ASHRAE 90.1 2004, which is based on occupancy profiles generated using large-scale building survey data and observations [17]. Such survey and observation based data are not only labor- and time-intensive to gather, but also inaccurate to reflect real space usage. For example, a profile for an office building assumes there are different periods of use (e.g., occupied from 9:00 to 18:00 for work days and not occupied at night and on weekends), but the periods during which buildings are partially occupied are not considered. These profiles depend on the type of building (e.g., office or education) and type of occupant (e.g., office workers). By using fixed design profiles, interior heat gain and cooling loads can be estimated. Based on the ASHRAE standard, the HVAC systems should be operated from 6:00 until 24:00, whenever there is a possibility of occupancy.

The ANSI/ASHRAE 90.1-2007 recommends HVAC schedules to follow the schedules defined for typical building types [18] and to be customized according to occupancy assumptions made during a building's design phase based on engineers' previous experiences, and large-scale occupant surveys [19]. Based on these recommendations, HVAC systems should run continuously when a space is occupied and be cycled on and off to meet heating and cooling loads during unoccupied hours [20]. However, studies have shown that occupancy patterns are stochastic in nature; thus occupant arrival and departure times are difficult to generalize and predetermine [21–23]. Researchers have found that actual occupancy of buildings differs significantly from the projected occupancy patterns that are used to determine HVAC schedules. This finding has been proven true in multiple test beds. For example, Duarte's data showed that occupants of an eleven-story business office building in Boise, Idaho, in northwestern United States, stay in the office approximately from 7:00 to 18:00, with a maximum occupancy load (heat generated by occupants) of 0.55 [19]. Wang found that occupants of a twenty-one-story office building in San Francisco, California, in western United States, arrive at 8:00 and leave before 21:00, with a maximum occupancy load of 0.75 [23]. Davis and Nutter concluded that occupants' presence in a two-story university building in Fayetteville, North Carolina, in mid-Atlantic United States, spans from 6:00 to 18:00, with a maximum occupancy load of 0.7 [24]. Mahdavi reported that presence of occupants in a high-rise office building in Vienna, Austria, spans from 8:00 to 20:00, with a maximum occupancy load of 0.6 [25,26]. Page et al. summarized that occupants of a laboratory building in Lausanne, Switzerland, are present from 8:00 to 18:00, with a maximum occupancy load of 0.65 [22]. These findings demonstrate considerable variations exist among occupancy patterns for different buildings in different locations. To reduce HVAC-related energy use without compromising occupant comfort, building-specific occupancy profiles should be taken into account for determining HVAC control schedules.

3. Review of previous research on occupancy-based HVAC schedules

To overcome the inefficiencies associated with using predetermined HVAC schedules, several researchers have used real time occupancy to optimize HVAC operations [27,28]. The idea is that energy use could be saved by not running HVAC in vacant zones. Substantial energy savings have been reported by prior research through not maintaining static setpoints in unoccupied zones [29–34], in which zone temperatures are allowed to float in different ranges, depending on whether the zone is occupied or not [35,36]. Agarwal et al. proposed different setpoints for vacant zones and occupied zones. In a simulation, temperature was maintained at 22.9 °C and 26.1 °C for occupied and unoccupied zones, respectively. The authors reported a 15% reduction of HVAC related energy use in a mid-sized office building [37]. By using an occupancy based HVAC schedule, Oldewurel et al. reported energy savings of 34% for a typical summer day in Switzerland [38], while Goyal et al. reported energy savings of 37% for a typical winter day in a city in the southeastern United States [39]. Although real-time occupancy-based HVAC schedules bring about energy efficiency, their implementation adds complexity to current control strategies and requires renovations or programming of existing equipment as accurate real-time occupancy monitoring must be instantly linked with HVAC programming. However, advanced building automation systems (BAS) and building energy management control systems (EMCS), which can monitor, integrate and program distributed building systems (e.g., VAV systems