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Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining

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ABSTRACT

The occupants' health, comfort, and productivity are important objectives for green building design and operation. However, occupant behavior also has "passive" impact on the building indoor environment by generating heat, CO_2, and other "disturbances". This study develops an "indirect" practical data mining approach using office appliance power consumption data to learn the occupant "passive" behavior. The method is tested in a medium office building. The average percentage of correctly classified individual behavior instances is 90.29%. The average correlation coefficient between the predicted group schedule and the ground truth is 0.94. The experimental result also shows a fairly consistent group occupancy schedule, while capturing the diversified individual behavior in using office appliances. Compared to the occupancy schedule used in the Department of Energy prototype medium office building models, the learned schedule has a 36.67–50.53% lower occupancy rate for different weekdays. The heating, ventilation, and air conditioning (HVAC) energy consumption impact of this discrepancy is investigated by simulating the prototype EnergyPlus models across 17 different climate zones. The simulation result shows that the occupancy schedules' impact on the building HVAC energy consumption has large variations for the buildings under different climate conditions.

1. Introduction

1.1. "Active" role of occupants

The occupants' health, comfort, and productivity are considered as key objectives for green building design and operation. At the same time, the occupants play a critical "active" role in the building operation. Occupant behavior and feedback are necessary to achieve the desired total building performance [1].

Numerous studies have developed various control systems and modeling methods to better assist occupants to play their "active" roles in buildings. Table 1 shows a summary of reviewed literatures of occupants' "active" influence in buildings. 10 out of 15 studies demonstrate an energy impact of occupant behavior by using various individualized control systems and dashboards for building heating ventilation and air conditioning (HVAC), lighting and plug load systems. Four studies about post occupancy evaluation and complain handling show the occupant feedback can be useful for building diagnostics. Another four studies show that providing occupants with individualized controls can influence their thermal comfort. Three studies show that providing the occupants with individual controls can improve their subjective satisfaction towards their working environment.

1.2. "Passive" role of occupants

The studies above suggest that the occupant's "active" feedback and behavior has strong influence on the indoor environment and building HVAC, lighting, and plug load system energy consumptions. Similarly, the occupant's "passive" role also has impact on the building performance. Particularly, for the building thermal and indoor air quality performance, occupants are treated as "mobile heat and CO_2 sources", which can influence the HVAC energy consumption to a great extent. Hence, the occupants are typically treated as "disturbances" in the HVAC control system. It is critical to study the occupant individual behavior and group schedule to uncover this "passive" impact.

The following studies show that the occupants "passive" behavior have a significant impact on building energy consumptions. The simulation study in Ref. [17] showed that "for a typical single-occupancy office room, compared to the standard or reference work style, the austerity work style consumes up to 50% less energy,

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Table 1
Reviewed literatures of occupants' "active" influence in buildings.

Studies	Building diagnostics	Energy impact	Satisfaction impact	Comfort impact	Health impact
Raja et al. – Availability of controls – opening windows and blinds [2]			●		
Veitch et al. —Cost-effective Open-Plan Environments Survey [3]	●				
Murakami et al.—Individual comfort votes [4]		●	●		
Loftness et al.—National Environmental Assessment Tookit [5]	●				
Choi—bio-sensing adaptive HVAC control system [6]		●		●	●
Lucid-Design —Dashboard on office appliances [7]		●			
Carrico et al.—Dashboard on office appliances [8]		●			
Daum et al.—Individual comfort votes [9]		●		●	
Gu—Knowledge-based personal lighting control [10]		●	●		
Klein et al.—Distributed comfort evaluation method [11]		●		●	
Yun et al.—Dashboard on office appliances [12]		●			
Park—Post Occupancy Evaluation [13]	●				
Goins et al.—Enhanced complaint handling process [14]	●				
Lee et al.—Agent-based approach to model active behaviors [15]		●		●	
Bonte et al.—Occupant action model [16]		●			

while the wasteful work style consumes up to 90% more energy." Ref. [18] conducted a simulation study on the occupant-controlled HVAC system in an open-plan office for the thermal and behavioral purposes. The study found that "when occupant sensors are used to reduce conditioning in unoccupied areas, energy consumption falls dramatically." The energy audit study in Ref. [19] on six randomly selected commercial buildings in South Africa suggested that "more than 50% of energy is used during non-working hours than during official working hours of 07:30–16:30 h". About 19–28% of the building energy went to the unoccupied hours of the weekends.

Numerous occupant behavior detection and schedule learning methods have been studied. The methods can be categorized as "direct approach" and "indirect approach" [20].

The direct approach is enabled by the latest development of information technology over the past few years, such as global positioning system (GPS), cellular data, wireless local area network (WLAN), infrared, radio frequency identification (RFID), ultrasound, Bluetooth, camera and LED (light-emitting diode) [21–25]. A few studies have applied some direct position technologies to learn occupant behavior and assist building controls. Table 2 shows a summary of this study.

Although direct positioning methods are effective to detect various building occupant behaviors, privacy can be a major concern for deploying these technologies in the real world. Therefore, less intrusive "indirect" occupant positioning methods are developed. Environmental sensor data mining, energy consumption data mining, and other stochastic modeling approaches are used in those studies. These methods are simulated or tested mostly for better controlling building HVAC systems with no or little personal information collected. Table 3 shows the summary of the studies that use indirect approach to model building occupant behavior.

1.3. Overview

This study aims to develop a less intrusive "indirect" data mining approach to learn the occupant "passive" behavior, and how it may influence office building HVAC energy consumptions in different climates.

A medium-size office building is used as the experiment test-bed. Wireless plug load meters are installed for the office appliances in the test-bed building. The appliance power consumption data is collected and used as training dataset to learn the occupant individual behavior and group schedule for the building. The individual behavior can be categorized into four types, "occupied computer-based work", "occupied non-computer-based work", "remote computer-based work", and "unoccupied". Several data mining algorithms are compared and tested to build the occupant individual behavior and group schedule prediction models. The learned occupancy schedules are compared with the occupancy schedules used in the Department of Energy (DOE) medium office prototype building energy models [40]. The EnergyPlus [41] model simulation results are compared between the two sets of models to discover the energy impact of group schedules under different climate conditions.

2. Methods

2.1. Data collection experiment setup

The experiment is set up in a medium-size office building—Phipps Center for Sustainable Landscapes in Pittsburgh Pennsylvania, US. 15 office workers in the open office spaces participated in the study voluntarily for three months from October to December 2013. Plugwise® wireless smart meters [42] are used to collect individual office appliance electric power consumption data for each occupant with a 5-min time interval. The metered office appliances include laptop computers, task lights, computer monitors, personal fans, chargers, and printers. The electricity metered data of office appliances are used to build the occupant individual behavior models and the group schedule models.

Ground truth data are used to train and validate the models. The ground truth data is collected with Fitbit® Flex™ pedometer [43] with its Bluetooth Dongle and a computer idle-time logging

Table 2
Direct approach of occupant behavior modeling studies in the building field.

Studies	Direct approach
Peters et al.—"Home gesture" to control lights, louvers, and blinds [26]	WLAN triangulation
Liao et al.—lower complexity graphical occupancy model [27]	Computer image processing
Zhao et al.—Fitbit® Zip™ occupant behavior modeling [28]	Bluetooth positioning
Bauereiss—smart phone application to control lighting systems [29]	Ultrasonic positioning
Shih—detect and track building occupants [30]	Computer image processing (image-based depth sensor and programmable pan-tilt-zoom camera)