Building and Environment 136 (2018) 77–87

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Understanding the recurring patterns of occupants' energy-use behaviors at entry and departure events in office buildings

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ARTICLE INFO

Keywords:
Office building
Occupant behavior
Energy-use patterns
Entry and departure events
Load disaggregation
Personalized energy feedback

ABSTRACT

Office-building occupants' behaviors during their arrivals and departures foreseeably have a large impact on a building's energy consumption since many occupants in control of appliances will turn their devices on or off at these entry and departure events. Consequently, occupants would have various types of energy-use patterns that coincide with their entry and departure events and that repeat over time. Despite the value that knowledge of such patterns would have on better tracking energy-use behaviors, these patterns have not been well explored with empirical data in the literature. Therefore, this paper studies occupants' energy-use behaviors in office buildings to identify and investigate energy-use patterns at entry and departure events. In particular, this research evaluates (1) the delay intervals that manifest between the occupants' entry/departure events and the beginning/end of the occupants' energy-consuming behaviors, and (2) changes in electricity consumption caused by occupants at entry/departure events to identify recurring—and thereby predictable—energy-use patterns associated with individual occupants. In the pursuit of this objective, the energy-use behaviors of 12 occupants in two office buildings were tracked during a four-month period. Results from statistical analyses performed on the collected data reveal that an occupant in an office building typically follows a consistent, recurring delay-interval pattern. In addition, the results show each occupant also follows a recurring pattern of power changes at entry/departure events. By identifying recurring, occupant-specific energy-use behavior patterns, this study significantly contributes to the current body of research and can be used to support research efforts into energy-load disaggregation.

1. Introduction

Even when compared to other major energy-intensive sectors—i.e., the industrial sector—the commercial sector has the highest energy-use intensity, and the rate of consumption is growing [1,2]. The commercial sector also typically presents higher-than-expected energy-use levels [3–5]. Within the commercial sector, office buildings are the largest subsector [6], and their total built area grows faster than other subsectors, including supermarkets and warehouses [7,8]. Currently, office buildings are responsible for more than 15% of the United States' commercial sector's energy use [9], and in the European service sector, office buildings have consumed 30% of total energy use since 1990 [10]. These data combine to prompt special attention from research and industry toward enhancing energy saving within this subsector.

While conventional approaches to energy savings focus on envelope retrofitting and system updates for enhancing buildings' energy efficiency—both of which necessitate large capital investments—a more cost-effective approach toward this goal focuses on intervening in occupants' energy-consuming behaviors [11–16]. Several previous studies [17–19] have demonstrated that such behavioral interventions among office building occupants show promise in enhancing energy efficiency in commercial buildings. In particular, offering individualized feedback (e.g., providing information about an individual occupant's energy consumption) has been shown to create better opportunities for prompting energy-saving behaviors as compared to group-level feedback in both residential [20,21] and commercial buildings [22–24]. However, the implementation of providing such feedback about occupants in commercial settings is still very challenging due to the cost and difficulty of obtaining individual occupants' personal energy-use data [16]. Currently, individual energy-use data in a commercial building is only obtainable through the installation of a plug-in sensor per appliance and/or occupant workstation, which requires high capital investments and configuration efforts [25,26]. Consequently, prevailing methodologies toward providing individualized feedback are cost

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https://doi.org/10.1016/j.buildenv.2018.03.037
Received 6 November 2017; Received in revised form 21 March 2018; Accepted 23 March 2018
Available online 26 March 2018
0360-1323/

prohibitive to most commercial buildings.

Non-intrusive load monitoring (NILM) approaches, which disaggregate building-level data down to the level of individual appliances, have risen as cost-effective alternatives for monitoring appliance-specific energy consumption. While the current prevalence of NILM indicates its success and feasibility [26–29], this approach is less effective in commercial buildings due to the number and abundance of similar appliances in use simultaneously. Additionally, obtaining individual occupants' personal energy-use data from NILM outcomes still requires linking appliance-specific energy consumption to occupants' energy-use behaviors (e.g., *who* is responsible for each plug load?) [16]. This characteristic is still very challenging to address and requires cutting-edge technologies and significant costs (e.g., attaching motion sensors to every occupant), which hinders NILM's advancement.

One possible opportunity to address this gap is to identify recurring/routine patterns of occupants' energy-use activities and harness such patterns to link monitored appliances with individual occupants. In office buildings, occupants typically work during specific working hours (e.g., 8:00 a.m. to 5:00 p.m.), which provides the foundations for discerning the occupants' recurring energy-use patterns. As occupants typically start using their appliances (e.g., personal computers) when they first arrive at their workstations/rooms each day (entry event) and end their energy consumption at their departure from the building (departure event), the on/off state changes of the appliances used by occupants predominantly align with the occupants' entry and departure events. Furthermore, such energy-use actions at the entry/departure events may include recurring patterns in terms of their timing and their quantity (magnitudes of power change) due to the routineness of office workers' behaviors and the limited set of appliances under use. Therefore, these entry/departure events foreseeably provide opportunities to identify which load-change pattern is related to which occupant—which in turn allows researchers to start disaggregating building-level data down to individual occupants. While revealing such recurring energy-use patterns of office building occupants would significantly benefit current research efforts in energy-load disaggregation and short-term energy consumption prediction, the existence of such patterns has not been adequately demonstrated/confirmed with empirical data.

Therefore, this study examines the recurring patterns of energy behaviors at the entry and departure events of office building occupants in order to link individuals with their habitual energy consumption. In particular, we identify recurring patterns in the relative timing and magnitude of energy consumption using empirical data collected in two buildings over a four-month period of time; these data are linked to the presence of individual occupants to identify which energy-load changes match which occupants. The significance of monitoring energy usage at occupants' entry and departure events is also reaffirmed.

2. Research background

2.1. Energy-load disaggregation in commercial buildings

Given that the most detailed level of electricity-consumption data for individual appliances and occupants is currently provided through individual plug-level power meters in commercial buildings—and these tools require a significant cost when applied to all appliances throughout a building—researchers have turned their attention toward more cost-effective tools, such as NILM. NILM presents a promising approach to providing disaggregated data at the appliance level with minimal costs [26,29,30]. In particular, NILM techniques identify specific signatures associated with appliances' operation from aggregate building energy data to disaggregate the data down to individual appliances. The majority of NILM techniques currently focus on residential buildings, and the application of NILM solutions is still limited in commercial buildings due to the multiplicity of similar appliances with similar signatures (e.g., multiple similar personal computers in a commercial office building). In addition, NILM techniques only provide the appliance's use information in commercial buildings and do not link this information to occupants' energy use behaviors. This limitation means NILM approaches typically fail to provide occupant-specific energy-use information in commercial buildings.

To economically estimate individual occupants' energy consumption, linking aggregate load data with individualized occupancy signatures (e.g. "Activity" level data on each occupant) could act as a solution with minimal uncertainty [16]. Currently, there are a few studies in residential settings that take advantages of using occupancy-sensing data in load disaggregation. Yoo et al. [31] utilized residents' location information collected through wireless sensor networks to disaggregate load in more accurate ways and to inform residents about their detailed energy usage. Paradiso et al. [32] used the information about residents' presence in houses to determine when devices were on and consequently to enhance the disaggregation of the whole-house load data. Shahriar et al. [33] used motion sensors to collect occupancy data to disaggregate energy-load data and to estimate the energy used by air conditioners in houses; the occupancy data determined when the air conditioners were in use. While such research did not directly deliver individual occupants' energy information and were mainly focused on residential buildings, their approaches to linking residents' activities with devices/consumption offer an interesting springboard for integrating occupants' activities into the load-disaggregation processes to economically estimate occupant-specific energy consumption.

2.2. Occupant energy-use pattern in office buildings

To acquire information about occupants' energy-consuming activities, researchers must first study the energy-use patterns of occupants. These patterns are defined as the presence of occupants in a building and their energy-related actions [34–36], such as window opening [37–39], light switching [40,41], and temperature changing [42,43] which influence the building's energy consumption. Numerous projects have studied various occupants' energy-use patterns in office buildings. Of these, several studies [42–52] investigated patterns such as adjusting clothing and opening windows in order to learn and predict occupant thermal preferences to optimize HVAC loading. Some researchers [36,53–55] also modeled variations in occupants' energy-use patterns to understand how changes in their preferences—such as thermal preferences—could affect overall energy use in office buildings. Other researchers studied individual occupants' presence within a building [35,56–60] to recognize, learn, and predict these patterns in office buildings.

Although researchers have examined and leveraged various energy-use patterns to better address energy-consumption habits, little attention has been paid to occupants' transient energy-use behaviors made right after they enter or right before they leave an office building. It is generally assumed that the energy-use behaviors of occupants at their entry/departure events have a significant impact on buildings' energy consumption. In particular, the state changes (e.g., on/off) of appliances used by occupants predominantly occur at the occupants' entry and departure events—several previous studies [61–63] indicated that the energy-use actions of office-building occupants predominantly happen at the occupants' entry/departure events. These high-influence behaviors could shift researchers' emphasis to occupants' actions at entry and departure events to gain a better understanding of office-building occupants' energy-use behaviors and accordingly to build more efficient behavior modeling and interventions for these behaviors. However, the stochastic nature of such energy-use behaviors at entry/departure events has not been adequately investigated with empirical data. While an occupant's energy-use behaviors at entry/departure events exhibit day-to-day variations in terms of energy-use magnitudes and relative timing to his/her entry/departure events, such energy-use behaviors may include recurring patterns that would significantly benefit current efforts into energy-load disaggregation. To this end, this research empirically investigates the existence of recurring energy-use