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Modeling plug-in equipment load patterns in private office spaces

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ABSTRACT

The uncertainty of plug-in office equipment choices and usage patterns is a major challenge in making proper design and control decisions by using building energy models. In this paper, the factors contributing to the plug-in equipment load patterns were investigated through an office equipment survey conducted with 203 participants, and the concurrent motion sensor and plug load data gathered in ten private office spaces. Results indicate that over 75% of the plug-in equipment electricity use in private offices takes place during unoccupied periods; and the plug load during the unoccupied periods exhibits a relationship with the duration of absence following departures. Drawing on these findings, this paper puts forward a data-driven model form to predict plug-in equipment load patterns in office spaces. The model is built on the plug-in equipment load patterns during five different time periods: (a) occupancy, (b) intermediate breaks, (c) weekday evenings, (d) weekends, and (e) vacations. The model inputs the predictions of an occupancy model and employs random sampling over the learned plug load patterns to generate plug load forecasts. The data gathered from the ten private offices were used to assess the accuracy and appropriateness of the model form. It was found that the models can accurately generate plug-in equipment load forecasts.

1. Introduction

Plug-in office equipment influences both the internal heat gains and electricity use—accounting for 13–44% of the total energy use in commercial buildings [1,2]. The uncertainty of plug-in equipment choices and usage patterns represents a major challenge in making proper design and control decisions that are based on building energy models [3,4]. For example, in order to predict the temperature response of a thermal zone over a prediction time horizon, a control-oriented building energy model uses weather and occupancy-driven forecasts [5]. If these forecasts do not consider plug-in equipment loads, the predictions can become inaccurate and the control decisions made upon them can become suboptimal. Similarly, a design-oriented building model in the absence of realistic plug-in equipment load schedules can result in misleading annual heating and cooling load predictions. This can inappropriately favor heating energy reducing strategies over cooling energy reducing strategies or vice versa, and cause improper heating, ventilation, and air-conditioning (HVAC) equipment or renewable energy system sizing.

1.1. Problem definition

In the current building energy modeling practice, the choice of plug-in equipment is implicitly reflected in terms of the equipment power load densities. The modeling guidelines inconsistently recommend a wide range of plug-in equipment load densities for office buildings. For example, DOE [6,7]'s reference office building model inputs a plug load density of $10.76\,\mathrm{W\,m^{-2}}$, whereas the building performance simulation tool eQUEST recommends $16.1\,\mathrm{W\,m^2}$. CIBSE Guide F [2] recommends using a plug load density of $25\,\mathrm{W\,m^{-2}}$ for typical office buildings. Alternatively, using 150 W per cubicle was recommended when the occupancy characteristics are known [2]. The ASHRAE Handbook of Fundamentals [8] recommends four different equipment power load densities ranging from 5.4 to $21.5\,\mathrm{W/m^2}$. After administering a survey with 92 energy modellers, Fuertes and Schiavon [9] reported that plug-in equipment load assumptions range from less than 10.8 to more than $32.2\,\mathrm{W/m^2}$. The same survey identified that about 80% of energy modellers used merely their experience while selecting the plug load values.

The usage patterns of the plug-in office equipment are currently represented in terms of equipment load schedules. For example, the default schedule for plug-in equipment loads in DOE [6,7]'s reference office building conservatively assumes that all plug-in office equipment are on during a cooling equipment sizing run; and they are all off during a heating equipment sizing run. In reality, it is

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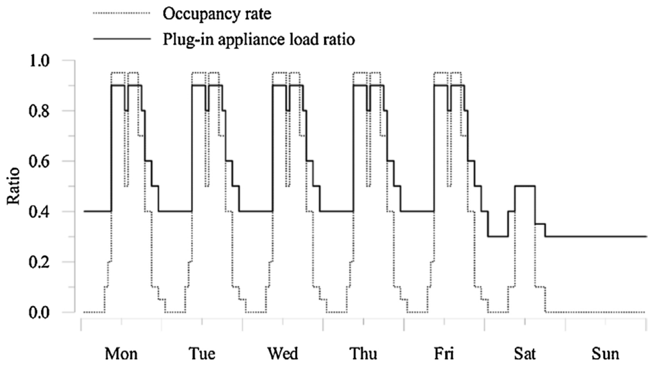

Fig. 1. Default plug-in equipment load and occupancy schedules of the DOE reference office building model [6].

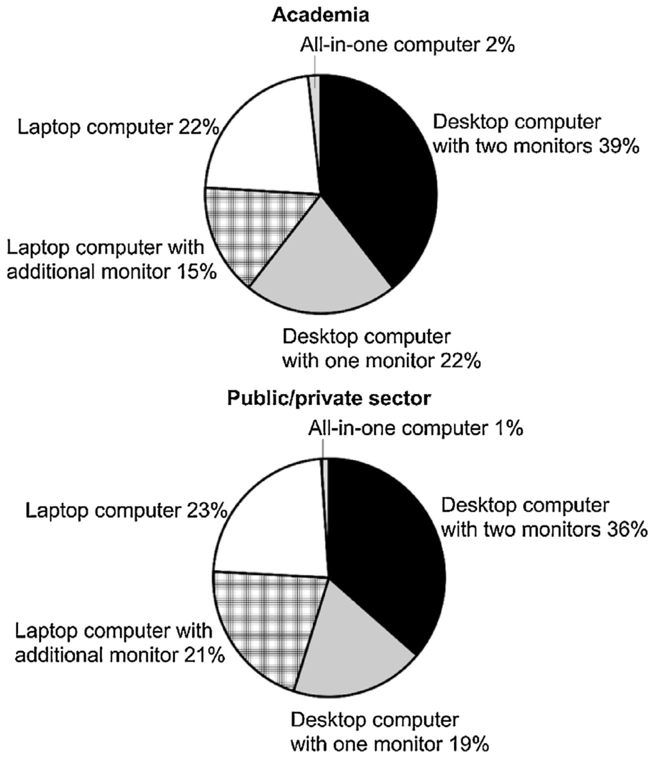

Fig. 2. Participants' responses to the survey item 1 (see Table 1).

rare to find all plug-in equipment completely on or off in an office building [10,11]. Evidently, this conservativeness leads to oversized HVAC equipment—and related part-load inefficiencies [12]. During an annual simulation run, the DOE reference office building model [6] inputs the weekly equipment schedule shown in Fig. 1—which is proposed upon engineering judgement in the absence of observational data.

1.2. Literature review

Computers and their monitors, photocopier, printers, and network equipment are common plug-in equipment in office buildings [13]. Computers and monitors are responsible for about 70% of the plug-in equipment electricity use in office buildings [10]. In an effort to provide better plug load benchmarks for building energy models, several observational studies about the office computer choices and usage patterns were conducted [3,6].

The power use characteristics of the computers have been evolving rapidly [1,14]. As newer computers mix with the older computers at an unknown rate, the equipment power demand characteristics in office spaces become more diverse. Consequently, the computer power demand values reported in the literature vary significantly. Desktop computers, when turned on, were reported to draw between 30 and 170 W; and this value was between 12 and 75 W for laptop computers [1,3,10,11,15–17]. This variability also puts the validity of rigid equipment power demand benchmarks into question.

Computers remain switched on only a fraction of the time. For example, Nordman et al. [15] observed that the computers were on 45% of the time on weekdays (10.8 h/weekday) and 20% of the time on weekends (4.8 h/weekday). After investigating the after-hours plug-in equipment states based on walk-through inspections in twelve buildings, Webber et al. [14] reported that more than 40% of the computers and 30% of the monitors were not switched off upon departure. Masoso and Grobler [18] conducted an energy-audit in five office buildings in South Africa, and reported that the energy use during unoccupied hours exceeded the energy-use during occupied hours. They attributed this to the fact that occupants tend to leave their lights and equipment switched on upon departure. In contrast, Kawamoto et al. [16] reported that manual switch off rates were 82% and 60% for the desktop computers and monitors, respectively. Also, it was reported that during nearly 50% of the regular business hours, the desktop computers and their monitors were idling.

The observational data presented in Menezes [19] indicate that the mean plug-in equipment load profiles in two different office buildings virtually do not change between 8 h00 and 19 h00—suggesting that occupants are unlikely to turn off their computers during intermediate breaks. In contrast, before 8 h00 and after 19 h00 on weekdays, and on weekends the plug load decreases substantially. In other words, the length of the duration of absence following a departure may influence the likelihood of office equipment switch off behavior. In a different context, Pigg et al. [20] observed that the likelihood of a manual light switch off action prior to a departure increases as the duration of absence following the departure increases. This could be extended to occupants' use of computers as well; however, the plug-in equipment load patterns have not been studied with concurrently collected longitudinal occupancy data.

Another factor playing an important role in the plug-in equipment use patterns is the type of the office equipment. For example, after monitoring 61 desktop and 20 laptop computers in office spaces, Moorefield et al. [21] suggested that desktop computers tend to be left on for three times longer than laptop computers. This was also confirmed by Webber et al. [14]. However, the ratio of the laptop computer users to the desktop computer users in different office buildings remains unknown.

A contextual factor playing a crucial role in plug-in equipment usage was noted as the size of the office building. Roberson et al. [11] reported that after work hours, 50% of the computer monitors were switched off in small office buildings. This ratio was 35% and 24% in medium and large office buildings, respectively.

In an effort to reduce the idling time in plug-in office equipment, the power management systems (e.g., Energy Star by the U.S. Environmental Protection Agency [22]) that turn off or reduce the power usage of the idling devices have been introduced. However, it was reported that falsely switched off computers can lead to frustration due to temporary or permanent loss of work-in-progress [10,17]. Consequently, power management settings are often delayed or disabled by users, administrators, or active software or software updates (e.g., software that prevents computers to switch-off, when there is unsaved work) [14,23]. Along with the software-based power management systems, programmable power strips have begun to be used in office buildings to turn off idling office equipment based on a scheduled timer or motion sensor-based inactivity detection [17,24,25]. Despite being promising for rooms with rigid