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Prediction of plug loads in office buildings: Simplified and probabilistic methods

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ABSTRACT

To predict buildings' energy use, multiple systems and processes must be considered. Next to factors such as building fabric and construction, indoor environmental control systems, and weather conditions, the energy demand attributable to buildings' internal heat gains resulting from inhabitants, lighting, and equipment usage also needs to be addressed. Given this background, the present contribution focuses on plug loads in office buildings associated mainly with computers and peripherals. Using long-term observational data obtained from a continuously monitored office building in Vienna, we specifically explore the relationship between inhabitants' presence, installed power for equipment, and the resulting electrical energy use. The findings facilitate the formulation of both simplified and probabilistic office plug loads predictions methods. Thereby, the model evaluation results suggest that the non-stochastic model provides fairly reasonable predictions of annual energy use associated with plug loads. However, the stochastic plug load model – together with a stochastic occupancy model – outperforms the simplified model in predicting the plug loads peak and distribution.

1. Introduction

Office buildings' energy demand is significant. In Europe, total annual energy use of office buildings varies roughly from 100 to 1000 $\mathrm{kWh\,m^{-2}\,a^{-1}}$, depending on factors pertaining to location, construction, environmental control systems, as well as equipment types and use patterns [1]. Generally speaking, office buildings' energy demand is due to both provision of proper indoor conditions (e.g., heating, cooling, ventilation, lighting) and operation of office equipment. The latter energy requirement is particularly affected by inhabitants' presence and behaviour [2]. Plug loads play a significant role in office buildings, involving computers, peripheral devices, telephones, etc. A large fraction of office equipment is controlled by inhabitants [3]. Plug loads are suggested to account for more than 20% of primary energy used in office buildings, and this ratio is stipulated to increase by 40% in the next 20 years [4–6].

Reliable estimates of plug loads are important for adequate design decision making. Specifically, building performance simulation tools geared toward assessing buildings' energy and indoor environmental performance would benefit from reliable methods to estimate plug loads magnitude [7]. The current state of knowledge (including both available information in standards and typical simulation input assumptions) with regard to the prevailing plug loads in office buildings may be characterized as not fully satisfactory.

Recently, a number of efforts have been initiated to investigate typical patterns of inhabitants' presence and actions and their impact on building performance [8–15]. However, there are arguably few studies regarding prediction methods of the magnitude and pattern of equipment use in office buildings. As such, only few recent studies have gone beyond the use of typical profiles of plug loads, trying to provide a deeper understanding or models of plug loads for building performance simulation [16–19]. Given this circumstance, the present contribution empirically explores presence and plug load patterns of a number of inhabitants of a selected office. The objective is to formulate a general, coherent, and transparent method to estimate office buildings' plug loads using a number of basic assumptions. Thereby, both bulk (e.g., aggregated annual values) and detailed (i.e., time-dependent high resolution) electrical energy use patterns are considered, resulting in a simplified (aggregate) and a detailed (probabilistic) prediction method. Note that, given the very small scope of the underlying empirical data, the authors do not claim the general validity of the specific formulation of the proposed prediction methods. Rather, the aim is to document the proposed approaches and illustrate their promis-

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ing potential, which are to be further tested and refined via future – more extensive – cross-sectional investigations.

2. Approach

2.1. Setting, research questions, and nomenclature

The main objective of the present contribution is to explore the possibility of predicting plug loads of office buildings based on two sets of assumptions, namely the installed equipment power (specifically computers and peripherals) and the presence patterns of inhabitants. Put in general terms, we hypothesise that plug loads or electrical energy use in an office building due to office equipment can be estimated based on installed equipment power and the presence patterns of the office inhabitants.

To provide both a concise illustration and an initial test of the proposed predictive approach toward estimation of office buildings' plug loads, we selected an office area in a University building in Vienna, Austria. The area includes both single-occupancy and open-plan office rooms/zones (see Table 1). The office area is used by eight regular staff members (referred to here as U1–U8) of different backgrounds (Department director, secretarial assistant, academic assistants, research scientists). The office area is equipped with a comprehensive monitoring infrastructure. Of importance are, for the purposes of the present contribution, sensors for occupancy detection and plug loads monitoring. Specifically, plug loads associated with each inhabitant (computers, peripherals, telephones, etc.) are monitored on a regular basis. To obtain occupancy data, wireless ceiling-mounted PIR sensors with EnOcean technology are used. The PIR sensor sends a value of 1, whenever a movement is detected. If there is no movement in its detection field, the sensor sends a value of 0 every 100 s. Plug loads are measured via wireless energy meters, which measure active electrical energy by means of the current between input and output and transmits the consumption and meter reading over the wireless network. These sensors transmit a telegram within 20 s if the power status changes by minimum 10 percent. In order to facilitate data analysis, the resulting data log of occupancy and plug load was processed in terms of 15-min intervals.

In this paper, the primary analysis and the basis for model development are based on 15-min interval data (inhabitants' presence, plug loads) collected over a one-year period (2014). To assess the developed models' reliability, two separate sets of empirical data from the years 2013 and 2015 were complied. Note that the data included in this paper concerning the installed power of desktop computers do not directly reflect their nameplate values. Rather, they have been derived based on nameplate information according to the insights gained in previous studies. These studies suggest that desktop computers consume on average 14–36% of the rated values [2,20,21]. In the present treatment, we thus define a specific coefficient, which is to be applied to the nameplate values of desktop computers' installed power.

The collected data was analysed to address a number of salient questions:

- What is, in this case, the overall magnitude of annual person-related and area-related plug loads and to which extend are these values in agreement with respective default values in pertinent standards?
- What is the degree of diversity amongst the inhabitants with regard to presence levels and plug loads?
- Is there a relationship between the installed equipment power and the annual energy used for electrical equipment?
- Is there an overall relationship between an inhabitants' presence probability at his/her work station and his/her energy use for electrical equipment?
- Can one establish predictive models to estimate inhabitants' equipment-related electrical energy demand based on their: (i) installed equipment power, and (ii) presence probability at their workstations?

To approach these questions systematically and formulate suitable prediction methods, some formal expressions can be useful as per the following nomenclature:

$P_{j,i}$ Inhabitant j's presence probability (at the workplace) at time interval t_i
Q_j Installed (name-tag) plug loads at Inhabitant j's workplace
$Q_{e,j}$ Effective installed plug loads at Inhabitant j's workplace
$q_{j,i}$ Inhabitant j's actual plug load at time t_i
$F_{j,i}$ Inhabitant j's plug load fraction at time interval t_i ($F_{j,i} = q_{j,i}/Q_{j,e}$)
T Length of time interval

2.2. Two approaches to plug load prediction

In previous publications, we have argued that the choice of proper modelling methods in building performance simulation must take the pertinent deployment scenarios (types of queries, their purpose, and the stage at which they are formulated) into account [22,23]. We thus postulate that in the case of plug loads too, different computational approaches may be appropriate for different use cases. Specifically, two approaches are introduced in the present contribution. The first (simplified) approach aims as obtaining aggregate estimations such as annual plug loads in an office area or building given certain basic input data such as overall presence patterns (e.g., in terms of diversity profiles) and installed equipment power. The second (probabilistic) approach aims at emulating the stochastic nature of load fluctuations. Toward this end, high-resolution (empirically-based or stochastically generated) time series of office inhabitants are utilised. In the following, brief descriptions of these two approaches are provided.

2.3. The simplified approach

We hypothesise that plug load fraction is a function of presence probability as follows:

$$F_{j,i} = f(p_{j,i}) \quad (1)$$

A linear version of this relationship could be represented as follows (with *a* and *b* as coefficients that would be empirically obtained):

$$F_{j,i} = a.p_{j,i} + b \quad (2)$$

Given these assumptions, the energy use associated with plug loads for an office with *j* inhabitants over a time period consisting of *n* interval with a length of *T* can be estimated as follows:

$$E = T \times \sum_{i=1}^{n} \sum_{j=1}^{m} \left(F_{j,i} \times Q_{e,j}\right) \quad (3)$$

For the office area investigated in the present study and using the empirical 2014 data, this relationship can be expressed in terms of the template provided by Eq. (2) as follows:

$$F_i = 0.53 \times P_i + 0.09 \quad (4)$$