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Occupant workstation level energy-use prediction in commercial buildings: Developing and assessing a new method to enable targeted energy efficiency programs

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ABSTRACT

As buildings become more energy efficient and automated, the role of occupants becomes more significant to assist buildings in reaching their full energy efficiency potential. Predicting occupants' consumption behavior has been identified as one of the most challenging processes in energy efficiency programs and building management system operations. Thus, more accurate behavior learning algorithms for commercial buildings are needed to improve energy efficiency. In this paper, we propose a method to predict occupants' energy-use behavior based on individual energy consumption profiles and assess its potential to increase the effectiveness of energy efficiency programs. The proposed method implements a support vector machine in order to model and predict occupants' short term energy-use patterns and test hypotheses for the existence of a correlation between occupants' entropy, efficiency and prediction accuracy. The results show an average accuracy of 83% for individual energy-use pattern prediction while being positively correlated with individuals' energy-use behavior. The main contributions of this paper are: (1) proposing and validating a new method to predict individuals' energy-use patterns based on their individual workstation-level energy consumption patterns, and (2) assessing the feasibility and potential of implementing this method to enhance the efficacy of energy efficiency programs to further induce energy efficiency.

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1. Introduction

The commercial building sector is responsible for a substantial portion of energy consumption in the United States. Recent research indicates that, despite technology improvements and tightened standards for this sector, the energy demand continues to grow at an annual rate of 0.8%; this is the fastest growth rate after the industrial sector [1]. The advent of advanced metering technology provides the possibility of building energy monitoring and feedback at various granularities. The most recent generation of wireless sensors facilitate the process of real-time plug load monitoring and feedback. Benefiting from the rich data acquired through these sensors, a thorough analysis on occupants' energy consumption [2,3], energy prediction [4,5], and eventually a more accurate bottom-up building energy prediction could be conducted [6]. This not only could increase energy managers' information about occupants' energy-use, but would also enable them to provide more accurate feedback to occupants and increase the energy efficiency of the building. Building occupant-level energy prediction could significantly improve energy efficiency (EE) programs by providing targeted, personalized, and timely information regarding occupants' behavior [7–13]. This information can considerably increase the effectiveness of such programs while providing a more pleasant user experience for EE programs (e.g. through eco-feedback systems). However, due to the high degree of uncertainty in predicting an individual's energy consumption [14,15], researchers suggest grouping these individuals to improve the prediction accuracy [16,17]. Yet, this recommendation is in conflict with the potential for advanced sensors to provide high precision and high resolution data (at the individual occupant level) on consumption in order to empower eco-feedback programs through targeting occupants, and enhance building management system control predictive models.

In this paper, we approach the occupant energy prediction challenge from a behavioral perspective. We propose a method to predict individuals' energy consumption behaviors at a workstation-level. We accomplish this by creating energy-use

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codebooks based on individuals' historical energy-use, assessing the feasibility of designing a targeted EE program, and introducing a new approach to maximize the effectiveness of EE programs in commercial buildings. Lastly, to validate our method we tested two hypotheses: (1) there exists an interdependency between energy-use pattern prediction accuracy and occupants' energy-use entropy, and (2) there exists an interdependency between energy-use pattern prediction and occupants' energy efficiency. The results of these tests are critical to assess the efficacy of our proposed method to target inefficient occupants in commercial buildings.

2. Related work

2.1. Sensor-based building energy monitoring

Sensor-based energy prediction has gained popularity in both the commercial and residential sector with recent advancements in sensor-based monitoring. However, the body of research is more focused on less granular scales (e.g. building, zone, city, etc.) [16–21]. High resolution sensors facilitate the implementation of bottom-up approaches which can potentially increase the prediction accuracy and provide diagnostics for identifying the areas of inefficiency in buildings [22]. Earlier datasets were captured at a relatively low resolution and building-level granularity, and energy prediction models were only capable of predicting building energy consumption at a high granularity [14]. Later, the metering technology was improved to a higher resolution by monitoring energy-use of central energy consumers in buildings such as HVAC systems, lighting systems, and domestic hot water systems [23–27]. Recent advancements in metering technology have provided an opportunity to meter end-user energy consumption at an appliance-level resolution. Despite these efforts on sensor-based energy feedback, there is still much research to be done to achieve metering infrastructure's full potential to induce energy savings.

2.2. Building energy-use prediction

In addition to sensor-based feedback approaches to understand energy use, various artificial intelligence (AI) approaches, such as machine learning algorithms, have been implemented to predict short and long term energy consumption of end-users in buildings. Early research in the commercial sector centered on ASHRAE's prediction competition in 1994. That year, MacKay [28] won the energy prediction competition by applying a Bayesian non-linear regression and an automatic relevance determination algorithm. The main focus later shifted toward Neural Networks (NN) and SVM-based algorithms, which represent more robust modeling approaches. Numerous researchers established novel modifications of NN models for energy consumption prediction. Adaptive artificial neural network algorithms [29] and feed forward neural networks [30] are variations that have already been implemented in the literature for energy prediction. However, algorithms are not necessarily the only impacting factor in occupants' energy prediction process. There is a substantial body of knowledge investigating the effects of various features impacting the training and testing of NNs. For example, Wong et al. [23] offered an energy prediction model by including building envelope type as a new input variable to train a model using artificial neural networks. The main differences in NN-based studies are in the input variables, architecture, parameter optimization, etc. In the residential sector, several similar studies on energy forecasting have been conducted. However, according to Edwards et al. [31] who examined various machine learning algorithms to predict residential electricity consumption, the different load shapes between residential and commercial buildings prevent the same algorithm from being effective in both sectors. Furthermore, Li et al. [32] compared the strength of SVM and NN algorithms in hourly energy prediction of cooling systems and found SVM as a more accurate algorithm in energy prediction compared to NNs. Moreover, Dong et al. [33] reported the advantages of SVM compared to NN as having a smaller sample pool, incorporating a structural risk minimization approach, and requiring a fewer number of parameters to be optimized in the training process. Therefore, researchers such as Fan et al. [19] proposed a data mining approach to develop the next-day energy consumption and peak power demand prediction ensemble algorithms. Ensemble algorithms benefit from a combination of ML algorithms to reinforce the learning process and combine multiple underlying basis models, including: multiple linear regression (MLR), auto-regressive integrated moving average (ARIMA), support vector regression (SVR), random forests (RF), multi-layer perceptron (MLP), boosting tree (BT), multivariate adaptive regression splines (MARS), and k-nearest neighbors (KNN). In this work, the ensemble algorithm prediction accuracy outperformed the individual algorithms. There are other advanced methods used to predict occupants' energy consumption in the residential sector such as [34,35]. Variations of Markov processes (e.g. Hidden Markov Model, Random Markov field, Markov chain, etc.) have been used to develop more comprehensive prediction models with the capability of considering prior, transitional, and emission probabilities in models. Among the aforementioned prediction methods, depending on the level of available information, type of data, and the length of data each method can outperform the others. Nevertheless, in this study due to incorporation of energy-use profiles, short length of study, and simplicity of SVM methods we decided to implement a support vector machine method for the sake of prediction.

2.3. Utilizing occupant-level monitoring to improve and target energy efficiency

There are a few studies that take advantage of high resolution end-user energy monitoring in residential and commercial buildings with a focus on energy analysis and energy efficiency. Chen et al. [36] utilized an appliance level real-time eco-feedback system to reduce energy consumption and analyze appliance energy-use in residential buildings. In a commercial building setting, Murtagh et al. [37] conducted an eco-feedback study with more than 80 participants, using historical comparison techniques to motivate occupants to save energy. Gulbinas et al. [2,38] investigated the effect of real-time eco-feedback systems coupled with various psychological techniques on occupants' energy consumption behavior in a commercial building. This study examined individuals' energy consumption at a workstation level and provided novel metrics and insights to quantitatively evaluate occupants' energy efficiency. Likewise, Bradley et al. [39] studied the effect of eco-feedback systems on individuals' energy consumption in an office environment. At a higher monitoring resolution, Yun et al. [40] designed an appliance-level eco-feedback system (e.g. main desktop computers and monitors, servers, modems, routers, refrigerators, etc.) to improve the occupants' energy awareness and efficiency through various psychological approaches. Coleman et al. [41] implemented an appliance-level personalized eco-feedback system to promote energy efficient behavior in commercial buildings. These aforementioned studies provide high resolution and personalized feedback such that each occupant can observe the energy-use information related to their own appliances and workstations. In some cases, this includes normative comparison approaches that allow monitoring peers' energy consumption as well. However, there are a limited number of studies that approached promoting energy efficiency in a targeted way to follow a "one size does not fit all" notion as endorsed by numerous researchers [7–13]. In other words, there

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