Applied Mathematics and Computation 234 (2014) 506–519

Contents lists available at ScienceDirect

Applied Mathematics and Computation

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

An analysis of the optimization disaggregation algorithm in the estimation related to energy consumption of appliances in buildings

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A R T I C L E I N F O

Keywords:
Energy use
Disaggregation
ODA
Accuracy
Unbiased
Convergence

A B S T R A C T

Generally speaking, energy monitoring system plays an important role in both energy use benchmarking and energy conservation service for large-scale buildings. However, it is often necessary for us to disaggregate the metered data according to types of energy use. Aiming at eliminating unclear concepts between monitoring and disaggregation and incorporating existing algorithms' advantages into the process in which this estimation is generated, the optimal disaggregation algorithm is developed. Based on the assumption of mutually independent ends, a Bayes process is degenerated into maximization likelihood estimation. Following this, the process is expressed by the least squares. With a new algorithm, an unbiased and overall convergent posterior estimation is provided for each terminal category, which is powerfully supported by theoretical analyses and numerical calculation. Actually, it is proved that the disaggregation algorithm is quite appropriate and cost-efficient for sub-item energy monitoring systems in large-scale buildings. Meanwhile, this thesis also focuses on discussing the conditional probability of overall lessening estimation errors specifically. In this way, posterior estimations of overall accuracy are available when prior estimations are concordantly biased with much different accuracy.

1. Introduction

As energy consumption intensity becomes increasingly high, large-scale commercial buildings have drawn more and more attention all over the world. Specifically, energy use of buildings accounts for about 30–40% in the total use of national primary energy in both developed countries, for instance, United State [1], and developing countries, for example, China [2,3,7,8]. Therefore, it is quite significant to observe energy consumption in such buildings. However, most of existing records, for instance, the EnergyIQ database [4], only relate to annually accumulated data in different functional buildings in a certain state or country. It is no doubt that this is not enough for understanding of what really happens in large-scale buildings.

In order to observe performance about building energy consumption in details, the energy monitoring system has been applied to a number of large-scale buildings in recent years so that it has become a hotspot [5,6]. The building energy monitoring system not only meters main circuit but also measures all branch circuits in use. Thus, most of terminal end use can be realized directly and effectively. The sampling period is about 5–15 min, in which the monitoring system outputs data accumulated hourly to users. With the help of the monitoring system, it is possible to observe details about energy

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http://dx.doi.org/10.1016/j.amc.2014.02.055
0096-3003/

performance of each appliance per hour, which enables energy assessment and diagnoses to be easy. On the basis of standard energy classification of ISO Standard 12655 [9], the building energy monitoring system can be an international platform that collects data from various types of buildings at different countries. In this way, energy comparison and analysis are available among a great many of buildings with the same function, which not only provides a global view of building energy use but also lays a foundation for energy benchmarking and diagnoses [26–33].

Regardless of foregoing advantages, direct sub-metering of the building energy consumption has its weaknesses. Researchers want to classify terminal energy use according to some standard energy models. For example, the terminal energy use is required to be filed based on their classifications like lighting energy use and HVAC energy use etc. Commonly, the sub-metering result fails to satisfy this requirement. The reason for this is that the function classification of the branch circuits in real buildings has not been clear. A circuit often contains terminals with different functions. For instance, a circuit of an office room usually consists of lighting, various plug loads, and air-conditioning fans. Indeed, scores or even hundreds of such appliances included are in a terminal circuit so that it is impossible to meter all appliances in such a large-scale building. Unfortunately, the mixed circuit data without details related to terminal appliance is nearly useless, for the comparison among mixed circuits with similar names but quite different compositions makes no sense. Consequently, the monitoring system should provide database of end uses according to the standard classification instead of end use of every electrical circuit. Then, as a typical inverse problem, the issue how to disaggregate the main circuit energy use into several kinds of end-use based on the sub-metering results of branch circuits with mixed functions comes into being.

It was in the 1980s that the research centering on testing and analyzing the operational behavior and energy performance of appliances in a single building began. However, it only focused on houses. Various kinds of high-frequency information monitored by the smart meter can be applied to identify the operational behavior of each appliance such houses, which acts as a non-intrusive load monitoring (NILM). Hannu Pihala [10] identified starting and shutdown process of each appliance by power changes in both active power and reactive power whose sampling frequency was 1 Hz. As electric meter technology develops rapidly, medium order harmonics of 10–15 kHz [11] and very high order harmonics which are greater than 1 MHz [12] have been applied to the field of terminal appliance identification. With such newly developed technologies based on NILM of appliance identification and disaggregation, a large number of smart meters with inner calculations and data storage have been widely applied to large-scale buildings [13–22]. Additionally, conditional demand approaches (CDA) was reviewed as a regression model to avoid the difficulty existing high order harmonics [23]. The conditional demand model which has a looser sampling period (1 s–1 min) not only collects information about equipment, for instance, rating power capacity of each appliance, as prior inputs but also estimates energy use of each appliance by virtue of the regression process. Both of the two approaches, NILM and CDA, concentrate on distinguishing the energy use of every appliance from records about the branch circuits. Based on this, it is known that they will become invalid when the number of terminal appliances increases and the sampling period enlarges to 5–15 min.

Akbari [24] developed an end-user disaggregation algorithm (EDA) by which he processed hourly electrical load data in a building based on simulation and proration. The algorithm established by him calculates relative energy and irrelative energy of climate, and then adjusts the two components in accordance with the proportion of their standard deviations. Although EDA cannot disaggregate total energy use into all kinds of appliances, it indicates Bayes approach which is a common methodology related to energy disaggregation issue. In fact, Bayes conditional demand model has been studied in order that a better posterior estimation based on CDA can be made [25]. Though their work focuses on house energy disaggregation, it contributes a lot to solving the problem in large-scale buildings.

Considering the fact that each kind of terminal appliance has independence, the Bayes approach can be greatly simplified and degraded into the method of Least Squares. This paper introduces a new disaggregation algorithm, hoping to offer powerful support for the energy monitoring system in large-scale buildings. Offering a posterior estimation method given prior expectation and standard deviation of energy use of each kind of terminal appliance, the algorithm proposed in this paper is fast, cost-efficient and well suitable for large-scale buildings. At the same time, this paper also presents a comparison among this method and other algorithms and discusses the range of its application.

2. The optimal disaggregation algorithm

2.1. Statement of the problem

With the aid of building electricity monitoring system, the energy use of branch circuits is available. However, several types of appliances like lighting, computers and fan coil units are mixed in most branches. It is rather difficult and costly to monitor all of the terminal appliances directly. Then, the energy disaggregation problem is developed. In another word, given a branch circuit (Y) with several kinds of end-users ($X_i,\ i = 1, \ldots, n$), its total energy use is known as $Y = y$. Solve the energy use x_i of each kind of end-user X_i. Apparently, it is unable to solve this disaggregation problem with n unknown variables by using the only one equation $y = \Sigma x_i$. Thus, it is essential to regard some terminal information as prior inputs in order to support a self-contained disaggregation problem. At least, $n - 1$ independent prior inputs should be supplemented to ensure the problem is full rank. Therefore, definitions of algorithm to disaggregation are developed as follows on the basis of maximization likelihood probability.