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An energy performance evaluation methodology for individual office building with dynamic energy benchmarks using limited information

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HIGHLIGHTS

- This study developed dynamic energy benchmarks for individual office building.
- Less information was used to establish the energy benchmarks.
- Four energy benchmarks were established according to four power consumption patterns.
- Comparative analysis was conducted between energy baseline and dynamic energy benchmarks.
- The evaluation results of energy baseline were improved using the proposed dynamic energy benchmarks.

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ABSTRACT

A rational and reliable energy benchmark is useful for understanding and enhancing building performance while most buildings cannot provide sufficient information for a detailed energy assessment. This work presents a systematic methodology of developing dynamic energy benchmarks for individual office building with very limited information. Simultaneously, an energy consumption rating (ECR) system is established to provide vertical energy assessment for individual office building in a short time span, i.e. hourly. Based on the data produced by DOE prototype large office building model performed in the EnergyPlus environment, this study is conducted in three steps: (1) Step 1: Data preparation; (2) Step 2: Development of the dynamic energy benchmarks; and (3) Step 3: Evaluation of the dynamic energy benchmarks and ECR system. Based on the decision tree analysis, the system energy consumption is classified into eight patterns by few commonly accessible weather and time variables, i.e. outdoor dry-bulb temperature, relative humidity, day type and time type. Then, four energy benchmarks are developed according to four energy consumption patterns on weekdays. To verify the effectiveness of the proposed dynamic energy benchmarks, it is used to evaluate the building energy performance on September, October and November, respectively. Besides, comparative analysis is conducted between the energy baseline (i.e. the same benchmark is used for all energy consumption patterns) and proposed dynamic energy benchmarks. Accordingly, the hourly ECRs were calculated using energy baseline and proposed dynamic energy benchmarks, respectively. Results showed that the energy baseline can be improved by using the proposed dynamic energy benchmarks. And the proposed method is capable of evaluating the energy performance of information poor office buildings.

1. Introduction

Building sector occupies the lion's share of both energy and resources. Currently, the building sector constitutes about 40% of total energy consumption world-wide as well as 30% of global greenhouse gas emissions [1]. Previous investigation demonstrated that typical buildings consume 20% more energy than required due to inefficient operation procedures, non-optimal control schedules and unnoticed faults [2]. In recent years, building energy benchmarking has gradually become an useful technique because it can assess systematic energy behavior and help operation personnel to identify unnormal energy use and inefficient operation state. It is defined as a macroscopic level of performance evaluation, using metrics to measure the building energy performance relative to its previous performance or other typical

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buildings [3].

There is a large volume of published studies describing the role of energy benchmarking on building energy performance evaluation [4,5]. Tronchin and Fabbri [6] used three different simulation methods (i.e. operational rating based on energy bills, dynamic simulation with the DesignBuilder software, and simplified simulation with the Best-Class software) to analysis the energy performance of a single house in Italy. Florio and Teissier [7] employed a typology-based model to estimate the EPCs of a housing stock using insufficient energy use data. Menezes et al. [8] presented a case study about how the lighting, small power and catering equipment impact the electricity prediction accuracy. Kabak et al. [9] examined a "fuzzy multi-criteria decision making" approach to analyze the National Building Energy Performance Calculation Methodology in Turkey. Koo and Hong [10] developed a dynamic operational rating (DOR) system for existing buildings based on geostatistical approach and data-mining technique. It was proposed to solve the irrationality of the conventional operational rating system (i.e. the negative correlation between the space unit size and the CO_2 emission density). Park et al. [11] presented an energy benchmark for improving the operational rating system of office buildings based on various data-mining techniques. Jeong et al. [12–14] established an energy benchmark to evaluate the energy efficiency of residential buildings in Korea. The proposed method was more reasonable than the original benchmarks as it solved the irrationality of the original benchmarks from overall database. Nevertheless, efforts have been made to provide multi-level benchmarks from building level to system level, subsystem level and/or component level. Yan et al. [15,16] proposed a simplified monthly energy performance calculation method based on basic energy balances for information poor building. It can provide energy performance data of a building at multiple levels. Wang et al. [17] presented a detailed multi-level energy diagnosis method to identify poor energy performance of a building, which can provide weekly, daily and hourly diagnoses at the building level.

In addition, in the past two decades, many countries and institutions focused on assessing the energy performance of buildings by developing an operational rating (OR) system, such as Display Energy Certificates (DECs) of UK [18], Energy performance certificates (EPCs) of European Union [19], Energy Star of the US Environment Protection Agency [20], and Building Energy Quotient of ASHRAE [21]. These OR systems compare the actual energy consumption of buildings with that of typical building which can be referred to as an energy benchmark, and then evaluate the energy performance of buildings by calculating the ORs according to specific energy benchmarks. The OR is a numeric indicator of the amount of annual energy consumption, which can provide quantitative assessment on building energy performance by classifying the energy consumption into several grades. It evaluates the energy performance of building by comparing with other buildings which have similar category and located in the same climate region [22].

In a nutshell, previous studies on building energy benchmarking usually stick to the building energy performance in a relatively long-time span, e.g. annual (365 days) benchmarking [22] or monthly benchmarking [15]. However, the energy performance of every building is invariably changeable due to shifty weather as well as internal instability factors (e.g. occupant behavior, electric equipment operation), it is improper to evaluating the energy performance of individual building only using an annual average or monthly average. In addition, a detailed multi-level energy benchmark for building is very useful while it usually requires comprehensive information for model development such as sub-metering data and building design data [17]. However, most existing buildings are information poor buildings in which very few sub-meters are installed, especially for auxiliary equipment such as fans, lift and lighting [23]. It is also difficult and time-consuming to obtain detailed building design data in some historical buildings. On the other hand, it is clear that the OR system is widely used to provide a reliable and fair energy assessment for buildings in many countries. Generally, the OR is employed to give a horizontal energy evaluation for buildings which have different energy performance, as it compares the energy consumption of a given building to a typical building. There is less discussion about developing a similar rating system for individual building, which can provide a vertical energy evaluation by compare the current energy consumption to previous typical energy consumption. Since the energy performance of building is very changeable due to shifty weather and internal instability factors, it is difficult to judge the reasons which cause drastic energy consumption variations for normal factors (e.g. shifty weather and occupant behavior) or faults. Hence, a reasonable and reliable energy benchmark is necessary for evaluating the energy performance of individual building. In addition, the rating system is a promising tool to provide a short-term energy assessment (e.g. daily and hourly) for individual building. Most importantly, the energy benchmark should be established with less information in order to achieving positive generalization that could be used for most buildings.

According to above analysis, a knowledge gap has been identified: the individual building need proper energy benchmark for detailed energy performance evaluation while few buildings can provide sufficient information. Therefore, this paper proposed dynamic energy benchmarks and energy consumption rating (ECR) system to provide vertical energy evaluation for individual office building specially for information poor building in a short time span, i.e. hourly. The remainder of this paper is organized as follows. In Section 2, the framework of the proposed methodology is presented and each phase of the proposed method is introduced step by step. In Section 3, the energy performance evaluation results are analyzed and the comparative analysis results are presented. Conclusive remarks are given in the final section.

2. Methodology

The framework of the proposed methodology is illustrated in Fig. 1. It consists of three steps: (1) Step 1: data preparation. The building energy data was collected from DOE prototype large office building model and the initial database was processed using different methods. (2) Step 2: Development of the dynamic energy benchmarks. The processed database was classified into proper clusters using decision tree. Then, the dynamic energy benchmarks of different energy consumption patterns were established and validated. (3) Step 3: Evaluation of the dynamic energy benchmarks and ECR system. The energy evaluation results of three months (i.e. September, October and November) using dynamic energy benchmarks and ECR system were analyzed. Comparative analysis was conducted between energy baseline and proposed dynamic energy benchmark.

2.1. Step 1: Data preparation

2.1.1. Step 1.1: Data collection

To establish the database for developing the dynamic energy benchmark of the office building, EnergyPlus [24] is used as the simulation program to produce data in this work. In addition, we deployed a prototype large office building model developed by the Department of Energy (DOE) of the U.S., since the repository of DOE covers building types that directly characterize more than 80% of commercial buildings [25]. Moreover, there are 17 representative cities of the U.S. for selection, which stand for all possible climate locations according to the American National Standards Institute (ANSI) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) distinction of climate zones [25]. In this work, we selected Miami as the representative city, which represents ASHRAE climate zone 1A. It has a relative long air-conditioning season from March to November, while its wet and hot season usually begins during the month of May and continues through mid-October.

The DOE prototype large office building has 12 storeys with a