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Framework for Energy Performance Measurement of Residential Buildings Considering Occupants' Energy Use Behavior †

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Abstract: Buildings' contribution to global final energy use is about 30%, which makes them a primary focus for implementing energy-efficient measures. Building energy efficiency is an important consideration for residential buildings due to the significant environmental impact of energy consumption and the rising cost of energy. Estimating and optimizing a building's energy performance is an efficient method to reduce its environmental impact and cost. There exists a lack of accuracy in estimating the energy performance of a building due to approximations in the monitored data as well as a lack of consideration for occupants' energy use behavior. This study aimed to develop a comprehensive framework that assists in accurately estimating building energy performance considering occupants' energy use behavior. The framework proposed a scheme to collect occupant behavior data, such as occupancy patterns, appliance usage, and lighting conditions, through a living-lab setup and developing an occupants' behavior model that was utilized for more accurate building energy modeling and performance analysis.

Keywords: building energy performance; occupants behavior modeling; living-lab concept

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1. Introduction

Buildings' contribution to global final energy use is about 30%, which makes them a primary focus for implementing energy-efficient measures [1]. A significant portion of this energy is wasted due to inappropriate building envelope design and construction. Building energy performance measurements can serve as a basis for building owners to make informed decisions for enhancing building energy efficiency. There is a growing concern in the building industry about the gap between the projected energy performance and the actual energy performance of buildings [2]. Bridging this performance gap is crucial in achieving the goal of reducing energy demand and enhancing building energy efficiency. The difference between the predicted and actual energy performance is due to approximations in the data as well as a lack of consideration for occupants' energy use behavior [3]. Therefore, a comprehensive energy performance measurement framework can help to effectively assess and quantify the building's energy efficiency.

The term occupant's behavior refers to the actions and responses exhibited by individuals within the building related to energy use and comfort, which are influenced by factors that include climate, building envelope, building energy and services systems, indoor and outdoor environments, time of the day, occupants' age and gender, and physiological, psychological, social, and economic factors [4].

2. Literature Review

To address the complex nature of occupant behavior and its impact on building energy consumption, Sun and Hong [5] proposed a framework for quantifying the influence of occupants' behavior on the energy savings achieved through energy conservation measures. Meanwhile, Wang et al. presented quantitative energy performance assessment methods specifically tailored for existing buildings, considering occupants' behavior and all other relevant factors to evaluate the buildings' energy efficiency [6]. Furthermore, Balvedi et al. [7] conducted a comprehensive review of various approaches and strategies available for gathering data on occupant behavior. They explored how these methods can be integrated into building energy simulation tools by incorporating occupant behavior models. It is widely observed that incorporating actual data for occupant behavior in energy analysis yields more accurate results as compared to energy simulations run without considering it [8].

The International Energy Agency identified six parameters that affect energy use in buildings. These parameters include climate, building envelope, building energy and services systems, indoor design criteria, building operation and maintenance, and occupant behavior. Each of these parameters plays a critical role in determining the energy efficiency of residential buildings and strategies for improving energy efficiency must consider each of these factors [9]. In addition, Chen et al. [10] in their study emphasized the need for a holistic approach to measuring the energy performance of residential buildings that considers all relevant factors and their potential impacts on energy consumption.

Laaroussi et al. [11] in their study identified the major issues and key drivers affecting occupants' behavior through an evaluation of existing approaches and methods for occupant behavior analysis. Furthermore, this study proposed and developed different methods to assess and predict the energy use behavior of occupants with better accuracy where conventional techniques such as structured and unstructured interviews, questionnaires, etc., prove to be inadequate. The study also emphasized integrating energy feedback programs into the building energy performance processes.

Incorporating an occupants' behavior model in the framework provides a more realistic evaluation of energy consumption patterns and assists in providing valuable insights into the factors affecting the energy performance of residential houses. Chen et al. [12] reviewed the impacts of occupant behavior on building energy consumption and established that the actual occupancy and the interactions with buildings are the key influencing factors determining the building energy consumption.

3. Methodology

This research study proposed a framework to measure the energy performance of residential buildings that incorporates occupants' energy use behavior with the purpose of accurately quantifying the impact of occupants' behavior on energy consumption in residential houses. The framework consists of three steps. (1) energy audit and data collection; (2) occupant behavior modeling; and (3) building energy modeling and performance analysis.

3.1. Energy Audit and Data Collection

The energy audit and data collection step begins with an assessment of the residential buildings, identifying the key influencing factors that affect energy consumption in residential buildings. For the energy audit and data collection, a hybrid method can be adopted that involves surveys, interviews, and on-site measurements using instruments to identify energy consumption and building envelope parameters in residential buildings, and installation of sensors for real-time monitoring of thermal properties of a building, indoor and outdoor environmental parameters, and occupants' energy use behavior through the living-lab concept [13].

The living-lab concept is a research methodology that focuses on the needs of end-users and stakeholders in the development of complex solutions. It involves creating a real-life test environment to sense, prototype, validate, and refine innovative solutions that address specific challenges [14].

3.2. Occupant Behavior Modeling

Occupant behavior modeling plays an essential role in understanding and predicting the energy consumption patterns of the occupants in a residential building. In a post-occupancy evaluation analysis [15], it was observed that occupant behaviors, including dissimilar presence at home, diverse occupancy levels, and differences in the occupants' thermal preferences play key roles in actual energy consumptions. Occupant behavior modeling involves developing mathematical models that incorporate various factors such as occupancy, interactions with the building systems, and occupants' preferences. The data collected in the energy audit and data collection step can be used to develop the mathematical model. Occupants' behavior is complex and diversified and has a stochastic nature rather than a deterministic one [16]. Therefore, stochastic occupant behavior model can be developed to capture the complex and diversified energy use behavior of occupants and generate synthetic occupancy schedules and occupants' energy use patterns with more precision over time. Such a model can be used to generate occupancy schedules and occupants' energy use patterns by simulating and predicting future states based on the current state and transition probabilities which can then be incorporated into the building energy simulation tools.

3.3. Building Energy Modeling and Performance Analysis

Building energy modeling and performance analysis begins with the development of a detailed energy model of the residential building, considering its physical characteristics, such as building geometry and orientation, building materials, insulation, HVAC systems, lighting, and appliances, using the data obtained from the energy audit and data collection. The real energy consumption data and the occupants' energy use behavior data such as occupancy schedules and occupants' energy use patterns can be incorporated into the energy model of the residential building. An energy simulation tool can then be used to simulate the energy performance of a residential building, with energy use intensity (EUI) serving as a metric to measure its energy consumption.

4. Building Energy Performance Measurement Framework

The framework depicted in Figure 1 comprises three main steps. The first step, energy audit and data collection, shall be carried out by collecting data related to building energy consumption and energy use; this includes; the data related to building envelope components and parameters such as building orientation, walls, roofing system, windows and glazing, doors, foundation and basement, exterior cladding, roof and window overhangs, solar heat gain coefficient (SHGC), insulation, R-Value and U-value, visual transmittance, etc., and monitoring occupants' energy use behavior through questionnaires, survey, interviews, and real-time monitoring through IOT sensors and data-logging sensors. The second step is to develop an occupant behavior model to generate synthetic occupancy schedules and energy use patterns using the data collected through occupant behavior monitoring. The data collected in the first and second step is then analyzed to perform building energy modeling and performance analysis.

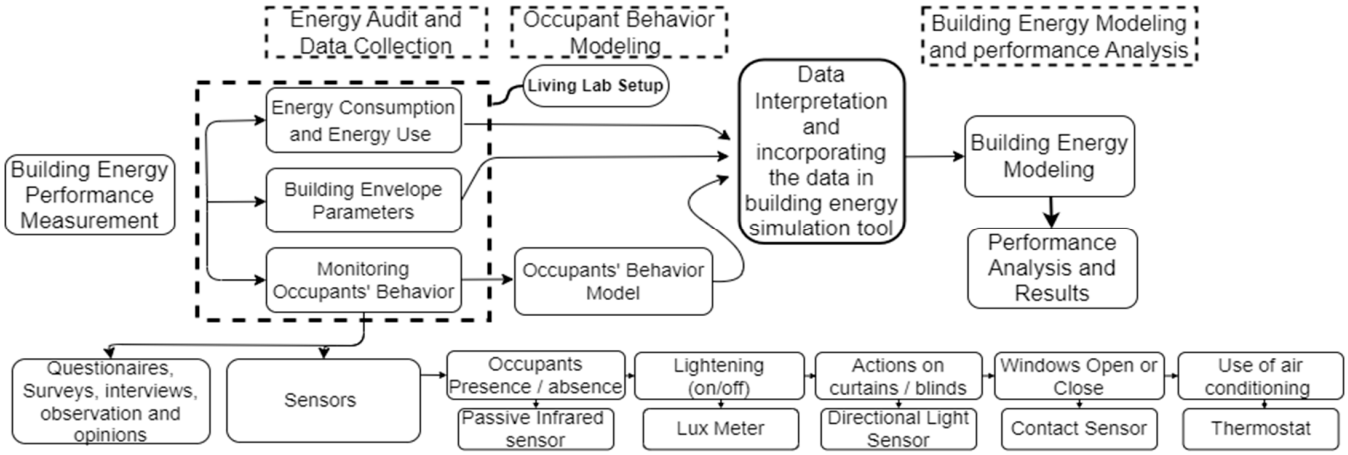

Figure 1. Building energy performance measurement framework.

5. Conclusions

This framework integrates an occupant behavior model, which can capture the complex and diversified energy use behavior of occupants. Therefore, this framework facilitates more accurate measurements of energy performance based on real-time data of the occupants' behavior and can enable the evaluation of different energy-saving strategies and the development of more efficient building designs customized to the occupant's behavior.

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