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Operation strategy of public building: Implications from trade-off between carbon emission and occupant satisfaction

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ABSTRACT

Large amount of energy is consumed to meet user satisfaction in public buildings, which causes carbon emission and results in environmental problem. A direct method to reduce this carbon emission is restricting opening area in public buildings. However, restricting opening area causes occupant satisfaction reduction. Trade-off carbon emission and occupant satisfaction needs to be concerned in building operation strategy design. In this paper, we developed a new integrated modelling method to trade-off between the carbon emission and occupant satisfaction of restriction strategies. We designed a case study in the sixth teaching building (STB) in Tsinghua University. Survey and field investigation were conducted to obtain data and build model. Integrated model result showed that satisfaction increases with the increase of carbon emission, while there exists cluster division and marginal diminishing patterns. By analyzing the performance of strategies with different calculation methods, we found that most optimal strategies open section B and C in STB. Meanwhile, when occupant number is 1,000, 2000 and 4,000, corresponding average satisfaction is 71.4%, 58.8% and 40.4%. It indicates that optimal operation strategy performance changes with the increase of occupant number, but the fluctuation is relatively mild. This integrated model has prospect in guiding energy conservation operation strategy design. It also supports real time monitoring and has potential in interactive platform application.

1. Introduction

Public buildings in China have high energy consumption intensity and results in high carbon emission. It was estimated that electricity consumption per unit area of public buildings equals to 2.5–3 times of residential buildings in China (Science and Technology Development Promotion Center of the Ministry of Housing and Urban and Rural Construction, 2016). Besides improving architectural design and upgrading devices, restriction on opening areas in public building is a direct and useful measure to reduce energy consumption and carbon emission (Liu et al., 2011). If rarely used areas are closed and users share services in fewer areas, energy consumption efficiency can be improved. However, occupant satisfaction will be lowered by the increase of occupant density and the limitation on occupant choice caused by restriction strategy (Fanger, 1988). Research has found that human habits and mindsets are the major barriers to energy efficiency policies (Nižetić, 2016). Therefore, balancing carbon emission and occupant satisfaction is an important issue of restriction strategy design.

Previous studies have provided several methods to analyze consumption and satisfaction. Estimations have found that the energy consumption reduction can be deduced through the influence of strategies on devices (Carriere et al., 1999; Min et al., 1999; Li et al., 2016), and satisfaction is related to complex factors (Astolfi and Pellerey, 2008; Frontczak and Wargocki, 2011; Cao et al., 2012). Surveys and models are widely used to quantify satisfaction. Previous satisfaction studies can be improved in reducing complexity and increasing practicability for guiding strategy design.

We conducted our case study of restriction strategy in the sixth teaching building (STB) in Beijing, Tsinghua University. All teaching buildings in Tsinghua University consume about 2,800,000 kW h of electricity annually, and among them STB consists of over 60% of the total electricity consumption. Research scope is defined as student self-studying behavior in STB on weekends. The influence of restriction strategy on satisfaction is determined by the

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disturbance of restriction strategy on decision-making behavior, included the choice of section, storey and classroom. The influence on energy consumption parameters involved changing usage of air conditioners, lights, water heaters, elevators, etc. Based on these data we constructed three models: an emission model that analyzed the carbon emission caused by energy consumption of devices, a satisfaction model that analyzed user satisfaction, and an integrated model that analyzed the optimization of these two factors. Strategies were evaluated by its effect on satisfaction and carbon emission. Suggestible strategies and common tendencies were found through further comparison. Model results can directly guide strategy designing by optimal strategy distinguishing.

Our research objective is providing practical tools for energy saving in public buildings, such as teaching buildings, libraries and public gym. Research reveals the relationship between occupant behavior and emission, which could help design energy saving strategies and shed light on future studies. Following the introduction section and the literature review section, we presented the conceptual framework and data collection method in section 3. In section 4 we sorted the device inventory, analyzed user decision-making path, and developed the integrated model. The result of modelling was represented and discussed in section 5.

2. Literature review

2.1. Restriction strategy

Closing certain areas and shut down related devices is a direct method to reduce building energy consumption and carbon emission in buildings. A daily example is closing the doors and turning off the lights of the unused rooms. When applied to public buildings, we define this method as restriction strategy. Many public buildings, such as teaching buildings, libraries and gyms, are divided into different parts with different usage rate. Restriction strategy is feasible in these public buildings, because if rarely used areas are closed and users share services in fewer areas, energy consumption efficiency can be improved. (Shen et al., 2015). Liu et al. (2011) studied the relationship between building occupant rate and energy consumption. The result showed that energy consumption per capita of lighting and heating dramatically drops with the increase of occupant rate. However, human bio effluents are concentrated when occupant rate increase, which will cause occupant dissatisfaction (Fanger, 1988). Research had also discovered that low air quality and high occupant rate reduce working efficiency of occupants (Wargocki et al., 1999). As so, the main barrier of restriction strategy is that energy conservation and occupant satisfaction contradict with each other (Fig. 1.). A trade-off between carbon emission and occupant satisfaction is inevitable, and question lies in how to design strategies that achieve higher satisfaction with lower emission cost (Voss et al., 2005).

2.2. Building energy consumption

Building energy consumption can be reduced by designing operation strategies. Through studying the influence of strategies on devices, consumption reduction potential can be deduced. Carriere et al. (1999) used a doe-2 model to analyze indoor device operation in different seasons. Solutions for energy reduction such as occupancy sensors and reduced ventilation air are tested, and the result showed that they had satisfactory effect on energy consumption reduction. Min et al. (1999) studied energy consumption efficiency in different building regions and offered suggestions for optimization through energy analysis. In similar ways, the effect of opening restriction on energy consumption could be reflected and analyzed. Li et al. (2016) conducted field investigations in northern China, sorted data of building devices and analyzed their usage condition. Devices are divided in separate systems, such as air-conditioning system and lighting system. Models of device operation were established to show the operation of devices in different operation conditions, and result indicated that large optimization room existed in lighting and heating systems. By using the tools offered by these studies, public building energy consumption and carbon emission can be analyzed and controlled.

2.3. Building occupant satisfaction

Occupant satisfaction is related to various factors. Some previous studies focused on the impact of physical parameters on occupant satisfaction. For example, Astolfi and Pellerey (2008) carried out survey on 51 secondary-school classrooms in America. Analysis through Pearson correlation showed that satisfaction was correlated with acoustic, thermal, visual environment, and air quality. Cao et al. (2012) analyzed air quality, indoor thermal and luminous parameters, using regression method to quantify the relationship between these factors and satisfaction with equations. In these studies, user satisfaction was directly related to environmental parameters such as air quality and lighting condition. However, these parameters do not include subjective factors such as personal preferences, working habits and requirement for privacy (Frontczak and Wargocki, 2011). As so, some other satisfaction analyses took the subjective judgments of occupants into account. Frontczak et al. (2012) collected questionnaire data from 43 021 occupants in 351 different buildings. In the questionnaire occupants were asked to rate the indoor environment condition by their subjective feeling. Responses on subitems such as visual and sound comfort are collected together with the general comment on indoor environment. The result of logistic regression analysis suggested that privacy is a main factor of occupant satisfaction as well as space and noise level. Schakib-Ekbatan et al. (2010) used a simplified questionnaire including six main factors influencing satisfaction, and applied regression to study the impact of subitems on overall satisfaction feedback. The result showed that other than physical conditions, work place satisfaction are also influenced by privacy, office furniture and office layout.

2.4. Trade-off between energy cost and satisfaction

Recently, a few researchers had started to integrate satisfaction analysis with energy consumption analysis. They aimed at trade-off between energy cost and occupant satisfaction and build models that are applicable for strategy design. Mostavi et al. (2017) developed an optimization model to minimize life cycle emission and maximize occupant satisfaction. Model input is feasible domains, unit initial costs and quantities, and the model can derive design solution output in terms of life cycle cost, energy consumption and indoor environmental quality. Wu et al. (2016) used a multi-objective optimization model in a case study in Hong Kong and derived suitable design solutions according to the result of modelling. Magnier and Haghighat (2010) applied artificial neural network method for the optimization of thermal comfort and energy consumption in a residential house· Occupancy and applied schedule were set as setting variables, and schedule performances were simulated and compared. Results showed that by applying this model several optimal strategies and patterns can be distinguished through performance comparison. All these studies used modelling as the tool for optimization performance evaluation. Also, case-specific quantification methods were used in these studies to enhance practicability.

Most of analyses above used multi-objective optimization framework, in which two or more dependent variables (e.g. energy