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Energy optimization of building design for different housing units in apartment buildings

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ABSTRACT

Current energy designs for a building in China focus on the energy efficiency of the whole building and thus often neglect the energy difference between different housing units in apartment buildings. The best design technique in terms of energy savings is not only to decrease whole building energy demand, but also to reduce the energy difference between different housing units to a relatively low level. This paper introduces an important index "energy performance difference between housing units" (EDH) to evaluate the drawbacks of conventional designs on a typical residential building in hot summer and cold winter zone. Then nine improved design options were considered as the possible strategies to diminish the EDH, based on a number of building simulations with the program DeST-h. Results show that the option 9 (add movable shading for the east facing windows and west facing windows, and reduce the *U*-values of the east walls and west facing windows), an improved design strategy according to the EDH of the current design, reduces the EDH to less than 4% that is much lower than other options and meanwhile ensures a decrease in whole building energy demands. A case study was carried out to validate the effectiveness of this index in optimization. As a conclusion, EDH is a very useful index for optimizing energy designs of apartment buildings and can be used in China to improve conventional building designs.

1. Introduction

The building sector in China is a huge consumer of energy and a significant contributor to greenhouse gas emissions. Recognizing the significant consequences of this energy consumption trend and environmental pollution, the government established several significant energy efficiency policies and mandatory standards for building design at the national, provincial, and local levels, such as "Design standard for energy efficiency of residential buildings in hot summer and cold winter zone" [1] and "Design standard for energy efficiency of residential buildings in hot summer and warm winter zone" [2]. These standards require a minimum energy saving of 50% for a whole building compared with buildings constructed in early 1980s, which usually includes many housing units, at the design stage by adopting energy-efficient measures. Thus, energy efficiency designs often focus on the whole building, neglecting the difference of energy between housing units in the building. For example, a 30 mm insulation layer are added to all external walls and Low emissivity (Low-e) windows are used on all facades without considering the different needs for levels of insulation and shading for walls and windows of different orientations.

However, due to fast urbanization and limits in land supply, most new built residential buildings in China are high-rise apartment ones (higher than seven stories), accounting for 97% of total residential buildings, with each floor having several housing units ranging mainly from 4 to 8 [3]. Thus, for a residential building there is usually more than 56 ($7 \times (4+8)/2 = 56$) housing units, which may locate in different orientations, on different floors or have different window–wall-ratios, etc. Hence, there may be a big difference in energy performance between different housing units in an apartment building even designed with a 50% energy saving for the whole building. This is because the different parts of building envelope may need different insulation and solar shading levels depending on solar radiation, building orientation, building shape, building geometry, etc. Therefore, simply used energy-efficient measures for the whole building energy efficiency target, without considering the difference in orientation, location, external wall area, etc. between different housing units, should be optimized to diminish these differences since dwellers should obtain the similar energy performance of different housing units if they behave in a similar way. Otherwise it is unfair for dwellers paying higher energy bills since they may pay the same money buying their housing units.

Numerous studies have been conducted on the optimization of building performance. For example, Magnier and Haghighat [4] carried out multi-objective optimization of building design using TRNSYS simulations, genetic algorithm and artificial neural network. Michael and Elijah [5] used a convergent pattern search algorithm with adaptive precision simulations to optimize building design, aiming to minimize the annual energy consumption of an

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office building. Ruchi et al. [6] developed a hierarchical design framework for optimizing building performance based on the analytical target cascading method. Wang et al. [7] applied multi-objective genetic algorithms for green building design optimization.

Cajsa et al. [8] estimated the impact of household features and building properties on annual electricity consumption in single-family homes using statistical analysis. Results show that variance in residential electricity consumption cannot be fully explained by independent variables related to household and building characteristics alone. Yu et al. [9] calculated the optimum thicknesses of five wall insulation materials with using solar-air cooling and heating degree-days analysis and P1–P2 economic model. Considering life cycle total costs, life cycle savings, payback periods, different orientations, surface colors, insulation materials and climates, optimum thicknesses of the five insulations is between 0.053 and 0.236 m. Later, they conducted a systematic evaluation on energy and thermal performance for residential envelope (EETP) [10]. The correlations between EETP and electricity consumptions were established in four cities in hot summer and cold winter zone of China. Results indicate that EETP method can provide possible measures to improve the energy efficiency for envelope designs of new buildings and retrofits of existing buildings. Essia et al. [11] coupled pseudo-random optimization techniques, the genetic algorithms (GA), with a simplified tool for building thermal evaluation for the purpose of minimizing the energy consumption of Mediterranean buildings. This algorithm is used to identify the best configurations from both energetic and economic points of view. However, these research focused on the improvement of whole-building energy performance.

Although few studies considered the energy performance of rooms in different locations of the same floor, optimization methods for reducing energy difference between different housing units have not been studied. For example, Yu et al. [12] carried out a simulation study on the low-energy envelope design of residential building in hot summer and cold winter zone. They compared the energy-saving potential of different envelope design options, including wall insulating, type of glazing, solar shading, area ratio of window to wall et al. They also analyzed the energy improvement of several strategies on different orientation rooms. The results showed that heating, cooling and total energy consumption for different orientation rooms differ largely.

No research, to the author's knowledge, has been done on the optimization of building design based on the energy difference between housing units in multi-story apartment buildings. Therefore, to make different housing units perform more close in the design stage, this paper gives a simple and new optimization method for reducing these differences based on the analysis of the drawbacks of current designs.

2. Methodology

2.1. Typical residential building

A typical twelve-storey residential building with one kitchen, one living room, one bathroom and two bedrooms in a housing unit located in Hangzhou, a typical city in hot summer and cold winter zone, was considered. The total gross area of the building is 1182 m^2, and Surface/Volume ratio is 0.28 and the height of each floor is 2.8 m. Fig. 1 shows the architectural plan of the typical residential building that has six same housing units on each floor. The only difference between the east/west housing unit and each middle housing unit is that there is a window on the east/west facade of the living and wash rooms, respectively, for the east/west housing unit while the living room only has a north facing window for each middle housing unit. The area ratio of window to wall is 15% for windows facing east, west, 27% for facing north, and 38% for facing south, which are average values obtained from a survey of 78 apartment buildings designed by nine different building design companies in recent 3 years in Hangzhou as shown in Table 1.

Since this apartment building is 12 storeys high with six housing units on each floor, the number of the total housing units reaches 72. Comparing the energy difference between each housing unit may take several days and is also not necessary because the energy performance for housing units with the same geometry at the same location on different floors is close to each other except at the first and top floors and thus the floors with the same housing units between the first floor and the top floor are usually modeled by a representative floor in building simulation software [13]. In this paper, the floors ranging from 2 to 11 were modeled by a middle floor having a floor multiplier of 10 to represent other nine middle floors for a great reduction of the simulation run time and housing units only on this representative floor were studied due to a large proportion of 85% (66/78 = 0.85) for which these housing units accounted.

2.2. Simulation settings

Typical energy-efficient construction materials were selected for the envelope design, which meets the Design standard for energy efficiency of residential buildings in hot summer and cold winter zone. The U-values of exterior walls, roof are 1.45 W/m^2 K and 0.97 W/m^2 K, respectively. The U-values are 3.2 W/m^2 K and 2.5 W/m^2 K, respectively, for double-paned, clear-glass windows facing east, west and north, and south.

The room temperature is set 26 °C for cooling and 18 °C for heating. The air conditioners, whose energy efficiency ratio (EER) is 2.3 when cooling and coefficient of performance (COP) is 1.9 when heating, are running throughout the year to meet the indoor temperature setting with the air change rate of 1.0 per hour, and the total power density of miscellaneous loads (including lighting systems and occupants) is 4.3 W/m^2. These settings are in accordance with the Design standard in this region [2].

The dynamic thermal simulation program DeST-h was used to evaluate the energy performance of the typical building. It was developed by Tsinghua University in China and validated by comparison with both well-known international thermal simulation programs and experimental results [14,15]. The typical meteorological year (TMY) data of Hangzhou city were obtained from China standard weather data for building simulation [16].

3. Energy performance of the typical building

3.1. Energy demands analysis

To estimate the energy performance of each housing unit on the representative floor, simulations were conducted and the results are shown in Figs. 2 and 3. Fig. 2 illustrates the cooling, heating and total (cooling and heating) energy demands for the whole building. It is clear that the cooling energy is almost three times higher than the heating one and the cooling, heating and total energy demand differences between the west/east housing unit and middle housing unit are big. To quantify these differences, the index "energy performance difference between housing units" (EDH) is introduced, it can be expressed as:

$$\mathrm{EDH}_k(i,j) = (E_{i,k} - E_{j,k})/E_{j,k} \times 100\% \quad (1)$$

where $E_{i,k}(E_{j,k})$ is the energy demand of the housing unit $i(j)$ ($i,j = 1,2,3\ldots,N$, and $i \neq j$), k denotes c, h or t, and N is the total number of housing units in the building.

Here EDH_t is used for the total energy difference, EDH_c for cooling and EDH_h for heating. Calculation of EDH between each