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The effect of spatial and temporal randomness of stochastically generated occupancy schedules on the energy performance of a multiresidential building

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ABSTRACT

Building performance simulation is frequently used to support building design, renovation, and operation. However, modelers are traditionally concerned with accurately describing technical input data, and have only limited interest in investigating the influence of occupant behavior on buildings' energy performance.

To fill this gap, this article examines the effects of stochastically generated occupancy schedules on the energy performance of a multiresidential high-rise building located in Shanghai, China. The building's energy performance is analyzed under two design proposals: a law-compliant proposal developed by the designers, and a second proposal conceived through an automatized optimization process. A statistical analysis quantifies the energy implications of adopting different degrees of randomness when creating occupancy and occupancy-dependent schedules.

Simulation outcomes show that temporal and spatial randomness of occupancy and occupancy-dependent schedules have a statistically significant influence on the building's energy performance, with an estimated uncertainty of up to 10%. At least in Shanghai, occupant behavior affects cooling more than heating, and its influence on the energy performance is stronger in high-performance buildings than in poorly insulated ones. Finally, accurate modeling of high-performance buildings would require a detailed and precise description of occupancy and occupant-dependent input variables even if this increases the modeling effort and costs.

1. Introduction

This article investigates the influence of occupant behavior on the energy performance of a multiresidential high-rise building located in Shanghai, China, and has its origins in the *Sustainable Energy in Cities* (SEniC) summer school organized by the Norwegian University of Science and Technology (NTNU) in collaboration with the Shanghai Jiao Tong University (SJTU) and held in Shanghai in July 2015.

The object of this study was chosen because, over recent decades, there has been a growing interest in reducing the environmental impact of the building sector, which is believed to be responsible for more than two-thirds of the world's primary energy usage and more than one-third of the world's greenhouse gas emissions [1]. Focusing on China, the International Energy Agency (IEA) and the World Bank state that China is currently the biggest greenhouse gas emitter in the world [2–4]. Furthermore, the US Energy Information Administration (EIA) claims that the Chinese building sector was responsible for up to 18% of the overall Chinese greenhouse gas emissions in 2009 [5]. Regarding energy demand, the EIA

Abbreviations: ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning; CO_2, carbon dioxide; $C_V(RMSE)$, coefficient of variation of the root mean square error; df, Degree of freedom; EBC, Energy in Buildings and Communities; EIA, Energy International Administration; HSCW, hot summer and cold winter; HVAC, heating ventilation and air conditioning; IEA, International Energy Agency; IWEC, International Weather for Energy Calculations; *MBE*, mean bias error; Md, median; Mtce, million tons of coal equivalent; NTNU, Norwegian University of Science and Technology; PSO, particle swarm optimization; PSOIW, particle swarm optimization with inertia weight; SEniC, Sustainable Energy in Cities; SHC, solar heating and cooling; SJTU, Shanghai Jiao Tong University.

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estimated that China is the largest energy user worldwide, with a rate of 18% in 2010 [6], and that one-fifth of China's total primary energy is attributable to the building sector. The IEA has also pointed out that China's residential and commercial energy usage were ranked respectively first and third among those of all the world's countries [2]. Additionally, it shall be recalled that, after the *Reform and Opening-up* policy launched in 1978, China entered into a frenetic period of rapid urbanization [7,8], with a level of urbanization that rose from 19.4% in 1980 to 53.7% in 2013 [9] and is expected to achieve saturation by 2030 [10]. This aspect is closely linked with the phenomenon of the rapid growth of the Chinese population, which increases the demand for residential buildings.

China's census indicates that energy usage has increased by more than 3.5 times from 1990 to 2013 (i.e., from 987 million tons of coal equivalent, Mtce to 3750 Mtce), while the amount of carbon dioxide (CO_2) emissions increased almost four times in the same period (from 2269 Mtce to 8106 Mtce) [11]. Berardi [5], elaborating data from IEA [12] and World Bank [4], pointed out that, in China, the energy requirement in 2050 will be 15 times higher than the level in 1970. In this scenario, some tremendous challenges related to environmental pressures, including energy usage and CO_2 emissions, have become more and more urgent in China [13,14].

Furthermore, as urbanization continues to increase rapidly, much still needs to be done to achieve energy security and environmental sustainability and to sensitize users' awareness of energy utilization. A study conducted by Murata et al. [15] showed that, in China, at least 21% of residential energy (up to 50% in some regions) may be saved by using household appliances with a higher efficiency. However, since the building standards' requirements are getting stricter, the relative impact of occupants on a building's energy usage is going to increase, and "better models of occupation presence and interaction are necessary" [16]. Indeed, the presence of people in a building affects its thermal and energy performance not only through the production of sensible and latent heat, but also, and to a large extent, through their activities and interaction with the building's systems, devices, and appliances. However, improper use of electric devices and appliances is a key factor that makes occupancy one of the weakest points of the energy balances of a building [17]. Wu et al. [18] compared electricity consumption, measured in 1999, among 410 apartments in Beijing and provided evidence that variations in household electricity use is mainly due to occupant behavior. In another study carried out in Beijing in 2006, Li et al. [19] monitored the summer use of air-conditioning in 25 identical apartments in a low-rise building. Outcomes showed relevant discrepancies in energy usage among these apartments, with a maximum value of 991 kWh per year and a minimum value of 170 kWh per year due to different occupant behaviors. Jian et al. [20] found a significant impact of occupant behavior on the whole electricity use in 44 individual apartments in Beijing. Regarding heating, Guo et al. [21], during the winter of 2013, monitored energy use for heating, indoor temperatures, and CO_2 emissions in 48 dwellings located along the Yangtze River (China) and belonging to the so-called hot-summer-and-cold-winter (HSCW) climate zone. Unlike Northern China, this region is not provided with district heating, and heating needs are managed at the building or even individual apartment level. Consequently, the operation time of each heating device varies significantly among different units and families' patterns of use. Measurements showed that the heating consumption was quite low, due to the fact that heating devices were used just for 30% of the entire heating season. Furthermore, indoor air temperatures, which reached on average 16 °C, were largely below any thermal comfort zone. In relation to all of the above-mentioned matters, one of the research questions investigated in this work is to estimate to what extent occupant behavior influences the energy performance of a multiresidential building while ensuring comfortable conditions.

It can be inferred from the aforementioned examples that, to fully characterize the performance of a building, several occupancy patterns seem necessary, shifting building modeling from a deterministic to a stochastic approach. Unfortunately, modeling occupant behavior is complex. Six typologies of models are available to describe occupant behavior[1]: psychological models, average value models, deterministic models, probabilistic models, agent-based models, and action-based models [22]. Focusing only on probabilistic models, different techniques can be used for developing these models, such as logistic regressions, state-transition analyses using Markov chains, Monte Carlo modeling, and artificial neural networks. Several reviews are available in the scientific literature that discuss the strengths and weaknesses of these models and techniques, for example Refs. [23,24]. Therefore, another research question consists of evaluating to what extent the (temporal and spatial) implementation of a probabilistic occupancy model in a simulation tool influences the energy performance of a multiresidential building.

Moreover, social, cultural, and economic factors provide a further significant contribution to defining occupants' attitudes towards energy usage in buildings. However, no occupancy model specifically built for Chinese society that was suitable to be used in the summer school was identified in the literature; hence, an occupancy probabilistic model developed for Japanese society [25] was implemented after a qualitative check was made regarding the reliability of its extension to the presented case study by the Chinese students and professors participating in the summer school.

In summary, this work aims at providing further insights into the influence of occupant behavior on energy uses for heating and cooling, electric lighting, and appliances by modeling stochastic schedules for occupancy and occupant-dependent input data in both a current law-compliant and an optimized design proposal for a high-rise residential building in Shanghai. However, in this article, occupant behavior is used exclusively to describe occupancy and occupant-dependent energy uses for electric lighting and appliances. It does not refer to the effect of those actions taken by occupants to manipulate the built environment to create more comfortable and pleasant indoor conditions, such as the operation of windows, solar shading devices, and thermostats, etc.

2. Methodology

During the SEniC summer school, three main learning outcomes were pursued to provide students with information and knowledge in the following areas: (i) numerical modeling and dynamic energy simulation of buildings, (ii) mathematical optimization techniques that are useful for supporting the design of high-performance buildings, and (iii) statistical analyses that are useful for interpreting the sets of data populated with the simulation outcomes due to the implementation of several stochastically generated occupancy schedules.

During the first week of the summer school, 15 students were split into two groups, which worked in parallel creating (i) the numerical model of the Base case, according to the law-compliant proposal developed by the designers and (ii) several stochastically generated occupancy schedules. Starting from the same blueprints, two subgroups, autonomously and in isolation, created two numer-

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[1] In general, these typologies of models allow a description of the occupant's status and action or reaction in response to external or internal stimuli in order to adapt ambient environmental conditions that can affect the energy performance of a building. However, in this article, only occupancy and occupancy-related energy usages are addressed.