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A stochastic model of integrating occupant behaviour into energy simulation with respect to actual energy consumption in high-rise apartment buildings

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ABSTRACT

Apartment buildings have evolved to be self-sufficient for occupants. Thus, energy use is individually controlled in apartment units, which can be considered as independent thermal zones within buildings. However, this has been disregarded in conventional energy modelling which is mainly applicable for reducing energy demands of buildings with standardised conditions, rather than reflecting actual consumption. This approach has been questioned due to the high levels of uncertainty formed with real buildings. In this study, a model considering occupant random behaviour consuming heating and electricity is developed to reflect variations in actual energy consumption in apartments. Moreover, the effects of various parameters of occupant behaviour in relation to the model were examined. In total 96 apartment blocks in Seoul were used as samples. Gaussian Process Classification was applied to modify occupant random behaviours corresponding to the probability of energy consumption. As a result, it has been found that occupants' general heating controls (25% deviation) are between three and eight hours, with 17–20 °C set temperatures. Moreover, the operating hours of electric appliances and lighting are also approximated with the probabilities. This methodology could reduce uncertainties in building simulations, and provide a broader application in buildings with similar development stages.

1. Introduction

Apartment buildings are one of the most common types of housing in Asia [1]. Their high capacity of accommodating a large number of residents has attracted the fast grown and growing countries, such as China, South Korea, Hong Kong and Singapore [1]. One of the representative countries for a great number of apartment construction, South Korea, experienced great economic growth in the 1960s, and the country became rapidly urbanised [2]. This urbanisation also resulted in a dramatically increased urban population [2]. Apartment buildings were introduced to accommodate this increased size of the urban population, particularly for the working class [3]. However, the main target for apartment buildings was gradually transferred from the working class, to the "new" middle class that rapidly grew during the economic growth in the 1970s and 1980s [4]. This transfer meant that living in apartment buildings became a representative of rising social status [5]. For this reason, the proportion of housing that were apartment buildings was much greater [6]. Seoul was one of the main centres in this significant transformation. In the 1970s and 1980s, 48% and 26% of national apartment construction was concentrated in Seoul, respectively [6]. They still comprised about 50% of housing in the city [7].

Improving thermal performance in existing buildings has been discussed in many countries [8] as carbon emissions is an international issue. Refurbishing old existing apartment buildings has been importantly investigated in Asian countries, such as [8,9]. In South Korea, apartment buildings built in the 1970s and 1980s have been highlighted due to their large population, as well as high energy consumption [7], in accordance with the intensified building thermal regulations [10]. Existing literature [11–16] has focused on reducing the energy demand of apartment buildings in standardised conditions defined by the Energy Performance Index [17] and Building Energy Efficiency Rating System [18]. These standards have provided deterministic conditions to identify changes in the energy demands of buildings. Thus, they have been used to verify energy efficiency in buildings, and guide buildings to improve

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their energy performance. However, this approach has been questioned in its relation of real situations. Many studies pointed out the limitations and uncertainties contained in the standard conditions of buildings used in existing literature [19]. One of difficulties in refurbishing existing buildings is the lack of interaction with the occupants [20].

Apartment buildings have evolved to be self-sufficient for occupants despite the unified features of buildings [5]. The usage of heating and electricity is individually controlled in each apartment unit, which can be considered as an independent thermal zone in these buildings. Therefore, energy consumption in apartment buildings can significantly vary. Besides, some empirical data in existing studies [21,22], showed variation in actual energy consumption in apartment buildings despite the similar thermal conditions. However, energy models with standardised conditions in the existing literature are not flexible enough to take into account the possible variations in energy consumption. Furthermore, the results would contain a high amount of uncertainty due to random behaviours of energy consumption.

Existing field studies have indicated how much energy consumption can vary by occupant energy behaviour. One of the existing studies [23] divided consumers living in the same apartment buildings by the heating consumption levels, due to the normality of the three distributions in the frequency density: lower than 500 kWh, 501–3000 kWh and higher than 3000 kWh. Except for the consumption of space heating, electricity consumption could also vary from 50 to 750 kWh among 100 households, and the consumption for standby was between 0 and 1300 kWh per year [24]. The monitored usage of electric appliances, apart from the consumption for space heating and hot water, was differed between 35% and 40% depending on the characteristics of the consumers' behaviours [25].

In order to take these variations caused by occupants' controls into building simulations, energy modelling in existing literature has attempted to integrate the variations with a probabilistic approach, rather than deterministic values. One of the probabilistic approaches is to use stochastic models. The concept of stochastic occupants' behaviours considers human behaviour as not deterministic, but complex and unpredictable actions which are represented by a composition of observable states [26]. Therefore, the stochastic model of occupants' behaviours takes the probability of actions which brings about energy consumption or a change in indoor environment. Virote and Neves-Silva [26] used the hidden Markov Chain model to integrate observable motivations of occupant behaviour taking the actions consuming energy. Nicol [27] considered occupants' behaviours as binary – heating on or off – and applied the probit regression analysis for modelling the proportion of occupants' actions in relation to outdoor temperatures. The stochastic models refine the ranges of possible consumption behaviours with the quantified probability. Therefore, the models draw uncertain factors with the more distinctive boundaries in building simulations. However, the limitations of stochastic models can be that they do not provide consistent results that can be directly input in building simulations [26], even the results are within the probable ranges.

This study, therefore, aims to develop a probabilistic model of occupant random behaviour consuming heating and electricity, regarding the variation in actual energy consumption for old high-rise apartment buildings. Three objectives are designed: to identify the variation in actual energy consumption in old high-rise apartment buildings built between the 1970s and 1980s; to integrate the variation in actual consumption into energy models; and to identify the possible occupant random behaviours controlling heating and electricity corresponding to the probability of energy consumption.

2. Methods

In order to identify probabilistic occupant random behaviours controlling heating and electricity the procedure was designed in four steps. At first, actual energy consumption in apartment buildings was surveyed, and then its variation was measured. Second, energy models of the random control of heating and electricity were analysed with their uncertainty. Estimated energy consumption of the energy models was optimised to reflect the distribution of the actual usage. Third, the probability of energy consumption was predicted by Gaussian Process Classification. At the same time, the possible ranges of occupant random controls were updated. Last, the probabilistic random behaviour was evaluated.

2.1. Evaluating variation in actual energy consumption in apartment buildings constructed in the 1970s–1980s

2.1.1. Sampling

There are many factors interrelating with energy consumption. Thus, it was important to control effects from unrelated factors in this study. Three sampling units were chosen: 1) locations; 2) physical conditions; 3) data availability. Firstly, the locations of apartment buildings were used to eliminate external effects. Sixteen apartment districts in Seoul were chosen. These districts were mainly developed for apartment constructions under an enforcement decree of the Urban Planning Act since 1976 [28]. Thus, apartment buildings in these districts were constructed in a similar time frame and near distance, which can minimise the difference in climate effects. Afterwards, these 16 districts were separated by socio-economic factors to avoid the impact of urban segregation in Seoul. Existing literature has identified that the disparities of education levels and occupations are highly correlated to the income levels of residents in Seoul [29–31]. Yoon [32] compared the geographical disparities of various indices related to the socio-economic factors: population, fiscal self-reliance ratio, health and welfare, education, prices of housing and land, industrial structure and transportation. Five boroughs representing relatively better living conditions were chosen from a total of 25 boroughs in Seoul by comparing a standard score of the indices. Residents with high level education were densely populated in these five boroughs. The robust correlation between the high-education residents in these five boroughs and their housing types (apartment buildings) has been found [33]. Sixtenn apartment districts are affiliated to these five boroughs. Four of the five boroughs (13 apartment districts), all with apartment buildings constructed in the mid—1970s and 1980s, were chosen for this study. The residents in the four boroughs, especially those who live in high-rise apartment buildings, were called "new" urban middle class [4,33]. Zchang [33] described the "old" middle class as small business owners and a higher income than the average. In contrast to the "old" middle class, Lett [4] discovered the seven categories of occupations in the "new" urban middle class in the four boroughs: scholars, government bureaucrats, corporate salary men, business owners, professionals, religious leaders, nouveaux riches. The life styles of the "new" urban middle class are varied [4,5], but people in this class can afford not to be concerned about energy consumption.

Secondly, the physical conditions of apartment buildings need to be constrained to avoid giving impact on energy consumption. Two of the most influential factors affecting energy consumption, thermal conditions of building envelopes [10] and heating methods [34,35] were chosen. Therefore, apartment buildings constructed in the 1970s and 1980s were divided into two groups depending on the thermal conditions of building envelopes, which were filtered by construction years. The first group, period A, was com-