Jang, H. and Kang, J. (2018) An energy model of high-rise apartment buildings integrating variation in energy consumption between individual units. *Energy and Buildings*, 158, 656-667

An energy model of high-rise apartment buildings integrating variation in energy consumption between individual units

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Highlights

- Energy model of high-rise apartment buildings developed by integrating apartments variation
- Average heating energy consumption limited in representing 96-171 kWh/m^2/year range
- Lower floors need higher set-point temperatures or longer heating hours than probable control

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Abstract

Building energy modelling methods have been required to be more accurate by taking into account variation in building factors affecting on energy consumption. However, modelling approaches for high-rise apartment buildings have often disregarded variation arising from individual apartment units. This study aimed to develop a building energy model of high-rise apartment buildings by integrating variation derived from individual apartment units. The methods were designed in three steps: identifying unit-specific heating consumption in different locations; creating a building energy model, based on the physical characteristics of apartment units and identifying the influential heating controls on heating energy consumption; and integrating a new set of polynomial model of independent heating controls in units and their interactions between floors. The result indicates that the averaged heating energy consumption of whole-building has a limited interpretation to represent the wide range of heating energy use in apartment units with different locations from 96 to 171 kWh/m^2/year. The integrated set of polynomial model found that apartment units on lower floors need either higher set-point temperatures or longer heating hours than the probable heating control in the building-scale. Moreover, the accuracy of the model estimation is also improved to CV RMSE 5.6%.

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1. Introduction

1.1 Integrated approach to building energy stock models

Energy consumption modelling of buildings quantifies an amount of energy required to preserve a comfortable indoor environment. As defined by Swan and Ugursal [1], various energy models can be used for determining regional or national energy supply requirements (macro-scale) as well as for measuring the efficiency in energy consumption of specific housing with refurbishment strategies (micro-scale). For the specific purposes of the macro-scale applications, building energy consumption models, which can also be called housing stock energy models [2], can help a decision-making of refurbishment policy and regulations with the cost-benefit analysis [2]. With micro-scale applications, the models provide impacts and energy saving because of specific materials and technologies.

Various methods have been shown: top-down, statistical and bottom-up, as reviewed in [1]. Pros and cons of these methods let us know which method needs to be chosen depending on a purpose of the modelling. The common methods of existing housing stock models are either statistical or engineering-based models. However, Booth et al. [2] pointed out the limitations of these common methods due to accuracy, data collection, computational time, decision-making and flexibility. Statistical models are less flexible but more accurate than engineering-based methods, whereas engineering-based methods are more extensive with computational simulations than statistical models [2]. The limitations are often derived from inherent uncertainties in building factors affecting on energy consumption in real situations.

The limitations of reflecting realities give rise to difficulty in comparing energy efficiency among different strategies and in choosing the most efficient option. In order to alleviate the difficulties, there have been continuous attempts to take the uncertainties into account with a framework of assessing building energy use for refurbishment measure. One of the attempt is an integrated method with a probabilistic approach. Heo et al. [3] attempted to infer probabilistic values of physical characteristics in buildings, in order to improve building energy models evaluating retrofit projects. The authors applied Bayesian Inference to calibrate the initial physical conditions of building energy models, based on the measured data of energy consumption. Booth and Choudhary [4] improved a decision-making framework from their previous work coping with uncertainties in housing stock models [2]. The authors mentioned that clustering housing stock was informative for decision makers applying refurbishment to a set of similar housings with specific types and conditions. Bayesian calibration adjusted average values of uncertain factors in each cluster to be similar to the measured values.

Building energy models, without considering an actual consequence of energy consumption, tend to overestimate their outcomes [5]. One of difficulties in refurbishing existing buildings is the lack of interaction with the occupants [6]. This disparity has been an obstacle to using model estimations for practical application. In order to reduce the disparity, various building controls in households [5] and actual consumption data [7] are essentially required. An empirical study, measuring the heating energy consumption in apartment units [8], showed significant variation depending on a location of apartment units and occupants living in the same building. This implies the necessity of the integrated approach into a building energy model for high-rise apartment buildings.

1.2 Existing housing energy models of high-rise apartment buildings

Residential buildings are divided into two groups depending on a number of floors: low-rise and high-rise. Low-rise residential buildings mean that the number of floors is less than three while buildings with more than four floors are considered as high-rise, according to building standards such as ASHRAE [9]. In mega-cities of Asian countries, high-rise residential buildings have been the most common type of dwelling [10]. The height of buildings has also been much higher than the four-story. For this reason, building energy models of these high-rise residential buildings have been limited to be specialised as a dwelling.

Statistical models, despite using actual energy consumption, are inflexible to provide accurate estimation for developing refurbishment policy in macro-scale as well as evaluating refurbishment strategies in micro-scale. It is because the statistical models only take into account the selected parameters, not consider the uncertainties and unselected parameters [1-2].

With the engineering-based approach, two methods of building energy models have been identified. The first modelling approach has been made on a premise that building occupants living in different units have unified building controls (heating and cooling systems). The building energy model with this approach mostly ascribed variation in energy consumption to the physical conditions of building envelope. Therefore, the model became radically simplified by only considering the physical conditions of the building envelope exposed to the outside with disregard to internal details, as shown in [11]. Alternatively, this approach can also build a model with only several representative units that are in adverse physical conditions for energy efficiency in the same building. These selected units with this approach are separately modelled and considered like detached houses [11]. The model comprised of the representative units provides specific energy consumption with a unit scale, but only for the selected units such as units on the ground and top floors. This is because the units on the ground and top floors present greater energy consumption than units on the middle floors. Human interaction controlling energy systems in the modelling approach mostly took the standardised condition although it is difficult to clarify [12].

Another approach also deals with the unit-scale modelling, but focuses on building factors inside of apartment units such as occupants [13]. Thus, this modelling approach often disregarded external impacts on variation in energy use arising from the diverse locations of units in high-rise apartment buildings. Moreover, internal impacts caused by an interlinked sharing slabs equipped with an under-floor heating system have also not been regarded in this modelling approach. The under-floor heating system in most of high-rise apartment buildings in South Korea, supplying heated water through the pipelines buried in the sharing slabs, is mainly controlled by apartment units on an upper floor having the sharing slab as a floor, while the slab also effects on the unit on a lower floor having the slab as a ceiling. The interaction to indoor mean temperatures through these slabs among apartment units has been identified [14].

Gelézeau [15] described the shapes of apartment buildings in Seoul as featureless and significantly unified appearance. She pointed out that the massive apartment constructions brought about the radical changes in the urban form of the city, Seoul. With these descriptions, building energy models with regard to physical characteristics of the many typical buildings can be somewhat useful enough to have rough estimations for these similar-shape residential buildings. However, it would not be accurate enough to be used for actual implementation, especially for existing buildings that necessarily need a calibration process of building energy models.

For these high-rise apartment buildings, the probabilistic approach was also applied to reduce uncertainties and calibrate the possible range of influential parameters affecting on building energy estimation. A previous study [16] investigated the possible range of occupants' heating controls with 17 – 20°C heating set-point temperature and 3 – 6 heating hours of heating for building energy modelling of existing apartment buildings in South Korea, constructed before 1980. However, the modelling approach disregarded the variation of individual units with different locations and occupants. Two issues can be discussed for this probabilistic approach. The first issue is a resolution of building energy models estimating energy consumption. The apartment buildings have been evolved to hand over controlling energy systems to occupants. However, the variation in energy consumption affected by occupants' controls has often been disregarded or easily generalised for buildings rather than individual units. Occupants' heating controls of the whole building with the district scale [16] could have a scope of the possible energy modelling for regional development rather than energy saving strategies for specific buildings. This is because that the resolution of the occupants' heating controls would not be specific for apartment units in apartment buildings. The second issue is the efficiency of probabilistic models on building energy simulations that require a certain value for influential parameters reflecting existing building conditions. Probabilistic models help to narrow down the possible range of the influential parameters and reduce the number of combinations that building simulations need to take into account. However, the probabilistic results may not bring a clear answer so that the required values of parameters can be read in different ways. This can reduce the reliability of the energy model estimation.

1.3 Aims of the study

As mentioned before, the method of building energy models is determined by a purpose of the modelling. Nowadays, the modelling method has been required to deliver more accurate reflections of realities. The previous section identifies that the current approaches of building energy modelling used for high-rise apartment buildings are limited to take into account variation in individual apartment units derived from the locations and occupants. This research, therefore, aims to develop an integrated approach for an energy model of high-rise apartment buildings. A framework of building energy models is established to reflect variation in the location of units and individual heating controls, based on actual energy use. 15 individual apartment units were placed in different vertical locations of a building simulation model to consider variation arising from the physical conditions. An uncertainty analysis with occupant-related factors was conducted to identify the impact on heating energy use in the building simulation model. Then, a new set of polynomial regression model was created to integrate the uncertainties identified from the occupant-related factors into the buildng simulation model. The process of the model framwork is inteperted in Section 2 and 3. The model demonstration is shown in Section 4.

2. Model framework

Figure 1 describes the conceptual model framework integrating variation in energy use derived from unit locations and occupants' heating controls in individual apartment units. It can be seen that the framework of the energy model is formed by three sections: (1) identifying heating energy consumption and its variation in individual apartment units with different locations; (2) creating a building energy model, based on the physical characteristics of apartment units in different locations and identifying the influential heating controls on heating energy consumption through uncertainty and sensitivity analyses; (3) integrating a new set of model for unit-specific energy consumption.

2.1. Unit-specific heating energy consumption of high-rise apartment buildings

This study intended to compare the unit-specific heating controls with the generalised heating control for the building with the same thermal conditions in the district scale [16]. The averaged energy consumption and the thermal conditions of the existing buildings were set the same as the previous study [16]. This study took the average heating energy consumption value in value in existing apartment buildings constructed before 1980, 123.2 kWh/m^2/year. For unit-specific energy consumption with this averaged heating consumption, this study applied a proportional rate of unit-specific heating energy consumption, which was produced by surveyed data from 57 apartment blocks constructed in the 1970s – 1990s in Seoul [8]. The rate was specified for fifteen-story apartment buildings with a unit size, 84m^2. Table 1 demonstrates the unit-specific energy consumption applied in this study. As shown in Table 1, vertical unit locations from the ground to the top floors showed a significant difference in heating energy consumption than the one among the horizontal locations among the west, middle and east sides of the floors. On average, 18 – 20 kWh/m^2/year standard deviation occurred due to the vertical location of apartment units. Horizontal unit locations showed a wider range of standard deviation from 2 – 15 kWh/m^2/year. Moreover, the consumption difference in the maximum and minimum among the vertical unit locations is 74 – 77 kWh/m^2/year, while the difference in the horizontal unit locations is 5 – 31 kWh/m^2/year. The possible unit-specific energy consumption in individual units in this study was generated for the vertical locations of apartment units, but the heating consumption in units on the same floor was used as the variation in calculating the mean and standard variation of energy consumption on each floor. The two values, mean and standard variation, used to calculate the possible range of energy consumption in apartment units with different locations by using random number generator in MATLAB R2015a [17].

Figure 2-(a) demonstrates the possible unit-specific heating energy consumption in apartment buildings constructed before 1980, which had the average heating energy consumption of the whole building is 123.2 kWh/m^2/year with standard deviation, 20.6 kWh/m^2/year. The possible unit-specific heating energy consumption in Figure 2-(a) indicates that the averaged value of heating energy consumption for the whole apartment building is limited to interpret the diversity of heating energy consumption in individual apartment units. As easily assumed, higher heating energy consumption on the ground and top floors, caused by the physical conditions, is clearly quantified. The highest heating energy consumption, 170.6 kWh/m^2/year, is occurred on the ground floor, followed by 146.8 kWh/m^2/year of heating consumption on the top floor as the second highest value. The other floors in-between the ground and top floors indicates a decreasing trend of the average heating

energy consumption in accordance with higher floors. There is a certain degree of fluctuation among the average heating consumption on these floors. However, the consumption from the first floor to the fifth floor is, overall, higher than the average consumption of the whole building, 123.2 kWh/m^2/year, while the consumption from the sixth floor to the thirteenth floor is, overall, less than the average. Heating energy consumption can be diverse depending on a level of standard deviation that exposes a level of dispersion on data. In other words, a building energy model for heating energy consumption can be easily failed if it does not take standard deviation into account. Especially, apartment units on the 5th and 8th floors in this study show the significant levels of standard deviations, 14.8 kWh/m^2/year and 11.4 kWh/m^2/year, respectively, while the average standard deviation is 6.6 kWh/m^2/year.

2.2. Consideration of the physical characteristics of apartment units in different locations

Building heating energy model was created to reflect the generalised conditions of existing high-rise apartment buildings built before 1980. As the same way of measuring the unit-specific heating energy consumption, the energy model also considered the vertical unit locations as the main focus of the modelling, whereas the horizontal unit locations were disregarded as uncertainties including occupants' independent heating controls. This is because the difference of heating consumption in apartment units on the same floors cannot be determined by totally the horizontal location, but interfered by occupants' independent heating controls although apartment units located on the sides of buildings may tend to have slightly more heating consumption. The building energy model was built to reflect not only the different vertical locations of units but also the internal thermal interactions through the sharing slabs. Firstly, the energy model was built by 15 units on different floors One unit was placed on each floor of the simplified model for the fifteen-story apartment building; the east side walls are connected to the lift halls, not exposed to the outside, as described in Figure 3. Secondly, the sharing slabs, equipped with the underfloor hot water heating, between two apartment units were built to indicate the thermal interaction between floors. District heating method was chosen not to give an impact due to the difference of heating methods, based on an empirical study [18]. Heated water could be circulated through pipelines buried in the sharing slab. A low-temperature radiant system (Zone HVAC: Low-Temperature Radiant Variable Flow) in EnergyPlus 8.0 [17] was applied in the energy model.

The profiles of the simplified energy models were intended to be the same with the previous study [16] for further comparison. Thermal properties of the building envelope were input to reflect the typical thermal conditions of apartment buildings constructed before 1980. The profile of thermal properties for apartment buildings was identified (Table 1 in [16]). U-values of building envelopes were input as shown: external walls (2.08W/m^{2}K); side walls (3.24 W/m^{2}K); roof (0.52 W/m^{2}K); floors (4.36 W/m^{2}K); windows (5.89W/m^{2}K). The details of occupants, lighting and electric appliances, were taken from the generalised conditions, identified from the actual energy consumption (Table 2 in [16]). The number of occupants was input four, which is the most common type of residents living in apartments. Lighting levels were identified for one apartment unit with 330.0W [20]. For electric equipment, five major appliances were input: TV (130.6W), refrigerator (40.0W), rice-cooker (143.4W – warming and 1022.9W – cooking), computer (263.3W) and Kimchi refrigerator (22.6W) [21]. Their daily schedules for lighting, computer and rice-cooker are taken from the results of the previous study [16]. The schedules of refrigerator and Kimchi refrigerator were set 24 hours, whilst 5 hours for TV [21].

Heating controls in apartment units were kept as uncertain factors. Two factors, independently controlled in apartment units, were mainly used: heating set-point temperatures and heating hours. 18 – 20°C for heating set-point temperatures was recommended in building regulations [22], whereas heating hours have not yet been officially provided. The heating hours in the conventional energy modelling were assumed to be 24 hours, and controlled by zone mean temperatures without considering occupancy. In this study, an uncertainty analysis was undertaken with the possible range of heating set-point temperatures from 16 to 22°C, and heating hours from 3 hours per day to 9 hours. In total 30 independent variables (2 variables of heating controls × 15 apartment units), and 15 dependent variables, heating energy consumption in each unit, were created. 150 random samples of heating controls for individual units were generated by LHS to conduct the Monte Carlo Method, which has been widely used in many studies for uncertainty analysis [23]. The sampling was managed by jEplus [24], and actual simulations were conducted by EnergyPlus 8.0 [19]. Historical weather file for 2014 generated for building simulations was acquired from [25].

Figure 2-(b) indicates the result of the simplified energy model estimations with the uncertainty analysis of the probable occupants' heating controls. The average value of the simplified energy model is 104.0 kWh/m^2/year (Figure 2-(b)) which is about 19% different from the targeted heating energy consumption (Figure 2-(a)), 123.2 kWh/m^2/year. However, the current simplified energy model (Figure 2-(b)) shows its vulnerability to the possible heating controls in individual apartment units and the limited interpretation of reflecting the targeted unit-specific heating energy consumption in Figure 2-(a). Therefore, the model needs to be sharply calibrated to reflect the targeted energy consumption in each apartment units.

2.3. Integrating relationships with individual heating controls in units and thermal interactions between floors through the shared slabs

Polynomial regression was conducted to create the new model of heating energy consumption specified by independent heating controls in individual units and their interaction between floors. This regression model is a type of multiple linear regression, but focuses one variable with curve fitting or two variables with surface fitting to improve predictions of mathematical models [26]. Therefore, heating energy consumption in each apartment unit can be modelled by considering two input influential variables.

Before the polynomial regression modelling, a correlation coefficient analysis was conducted to determine influential variables of heating controls for the unit-specific heating energy consumption in each apartment unit. The correlation coefficient values of independent variables were compared as they interpreted the strength of heating controls with heating energy consumption, and the directions with positive or negative values [27]. Heating set-point temperatures and heating hours for the 15 apartment units from the 150 samples were input as 30 independent variables. The heating energy consumption in the 15 apartment units was as 15 dependent variables. Pearson's correlation coefficient [27] was applied to measure the linear correlations of heating controls with heating energy consumption in the apartment units on the 15 floors. SPSS version 22.0 [28] was used for calculation.

The correlation coefficient analysis allows determining relevant independent variables in changing the unit-specific heating energy consumption in the simplified energy model. Figure 4-(a) shows the results of correlation coefficient analysis. The most significant determinant of heating consumption is the heating set-point temperatures in apartment units where heating is on with the correlation coefficient values distributed between 0.5 and 0.9, depending on the unit locations. The operating hours of heating also show positive associations with moderate correlation coefficient values between 0.1 and 0.4. Both variables effect on increasing heating energy consumption in apartment units.

Another significant determinant is the heating set-point temperatures on an upper floor, which have correlation coefficient values between -0.6 and -0.3. While the set-point temperatures and heating hours in apartment units where heating is on are the determinant increasing heating consumption, the set-point temperature on an upper floor is the one decreasing heating consumption. This represents that the interlinked relationship between floors through the shared slabs. Heating energy consumption in this energy model is dominantly associated with heating set-point temperatures in apartment units. However, operating hours of heating in apartment units and heating temperature controls on an upper floor are also important variables in calculating heating energy consumption. Consequently, the correlation coefficient analysis determines two correlated conditions for the unit-specific heating energy consumption. One is heating controls in apartment units where heating is operating (heating set-point temperatures and heating hours), another is heating set-point temperatures between floors.

This is also proved by R-squared values of polynomial models, as indicated in Figure 4-(b). These two conditions are integrated into the polynomial regression models to be used for further predictions: heating controls in each apartment unit (blue dotted lines in Figure 4-(b)) and heating set-point temperatures between floors (red dotted lines in Figure 4-(b)). Compared to the polynomial models with one variable, heating set-point temperatures (white dotted lines in Figure 4-(b)), polynomial models with two variables have higher R-squared values. Adding one more independent variable either heating hours or set-point temperatures on an upper floor raises R-squared values, indicating how well the data fit statistical models. The R-squared values of models with heating controls in apartment units are slightly higher than the models with heating set-point temperatures between floors. However, the different is not significant enough to disregard the impact of the set-point temperatures between floors.

3. Model establishment

In the previous section, the correlation coefficient analysis demonstrated the two significant determinants interpreting heating energy use in individual apartment units: individual heating controls and thermal interactions between floors through the shared slabs. Thus, heating set-point temperatures and heating hours in an apartment unit as well as their impact on the other unit sharing slabs equipped with the under-floor heating system. This section specifies the new model establishment of heating energy use in individual apartment units with respect to the two significant determinants.

Based on the correlation coefficient analysis, polynomial models were created by polynomial surface fitting in the Curve Fitting Toolbox in MATLAB R2015a [17]. The procedure of polynomial regression minimises the sum of squares of deviation from corresponding points [26]. Therefore, the goodness of fit in the polynomial models was measured by the coefficient of determination (R-squared values), representing how much data can be explained by polynomial models, and the sum of squared errors, indicating how much data cannot be fitted into the models.

The polynomial models in this study were defined by two conditions: heating controls in apartment units and heating set-point temperatures between floors. Different polynomial surface models were applied to create the best-fit models, and sought the dataset of heating controls in each apartment units determining actual unit-specific heating consumption. MATLAB allowed specifying the degrees for the inputs (Heating set-point temperatures and heating hours) up to five. As a result, the energy model was expected to be more accurate in calculating energy use not only for a whole building, but also individual units. Moreover, the dataset of heating controls in each apartment unit can be provided. For example, a polynomial surface model of heating consumption between floors was set as shown in Model I – V. Heating energy consumption in an apartment unit was interpreted by heating set-point temperatures in an apartment unit where heating is on and another unit on an upper floor. By controlling degrees of these inputs, the polynomial models were different, as below.

Polynomial models were developed by integrating two conditions, heating controls in apartment units and the interactions of heating temperature controls between floors. Firstly, various degrees of polynomial models from a linear to more complicated designs were evaluated by comparing the goodness of fit with R-squared values of models and Root-Mean-Square-Error (RMSE). Secondly, the best-fit models were used to calculate the sensitivities of two independent variables in order to achieve the targeted heating energy consumption in each apartment unit.

3.1 Polynomial models of heating controls in apartment units

Figure 5 demonstrates the determination of the set of polynomial model for heating controls in individual apartment units. Compared to the goodness of fit with linear models (red dots in Figure 5-(a) and (b)), complicated models would not present significant fit on the heating energy consumption. However, there are several floors, which present relatively better fit with complicated models (blue dots in Figure 5-(a) and (b)). Functions become more complicated in higher degrees of polynomial models, which would not be effective and accurate for calculations. Thus, the models are intentionally selected not to increase the degree of polynomial models, but with a higher rate of R-squared values and RMSE. Linear models could interpret the most unit-specific heating energy consumption with the greater rates of R-squared values and RMSE. However, four floors show relatively higher R-squared values and lower RMSE with the second-degree (quadratic) polynomial models: the ground, second, sixth and eleventh floors. One floor, the 12th floor, indicate the acceptable rate of R-squared value and RMSE with the third-degree (cubic) polynomial model.

Figure 6 interprets that heating set-point temperatures in the polynomial models of apartment units are variously determined to achieve the targeted heating energy consumption by changing heating hours from 1 to 12. The average heating set-point temperature in each apartment unit is distributed in the temperature range between 17 and 20°C. The average heating set-point temperature is getting lower in accordance with higher floors. The six floors from the ground to the fifth indicate the average heating set-point temperature around 20°C. The next five floors, which are the sixth to ninth and eleventh floors, show about 19°C of the average heating set-point temperature. Three floors, which are the 10, 12, and the top floors, have 18°C of the average set-point temperature. Only one floor, the 13th floor, shows about 17°C of the heating set-point temperature. Although the average heating set-point temperatures are distributed in the 90% of the probable range of the heating set-point temperatures (17 – 20°C) [16], the temperature range can be much more diverse depending on the heating hours. The most significant uncertainty is found on the ground floor. The heating set-point temperatures on the ground floor can be between 15 and over 24°C. The lowest set-point temperature can be occurred by the 12th floor, indicating between 13 and just below 20°C, depending on the heating hours.

Figure 7 demonstrates the change of heating set-point temperatures by increasing heating hours in the individual apartment units. The previous study with the whole building modelling estimated that 90% of probability of heating hours between three to six hours with 17 - 20°C of heating set-point temperatures [16]. The authors reclaimed that the average heating set-point temperature for apartment buildings constructed in the 1980s with 18°C rather than 20°C, which has been widely applied in the conventional energy modelling. However, the unit-specific energy models with polynomial regressions indicate that the estimation with heating hours from three to six hours can be partially correct, as shown in Figure 7-(a) - (c). Apartment units located in lower floors need either higher set-point temperatures or longer heating hours in order to achieve the targeted heating energy consumption. Specifically, energy consumption in apartment units on the ground to 5th floors requires more than seven hours of heating with the range of heating set-point temperatures between 17 - 20°C (Figure 7-(a)). In other words, heating set-point temperatures for these floors need to be risen up to 22 – 23°C with less than six hours of heating. The heating consumption on the 6 - 9 and 11th floors is distributed between four and nine heating hours with 17 - 20°C of heating set-point temperatures (Figure 7-(b)). The range of heating hours is achieved between three to eight for the consumption in apartment units on the 10th and 12th - top floors (Figure 7-(c)). The results indicate that heating controls in unit-specific energy models have the wider range of heating hours with 17 - 20°C of heating set-point temperatures, which showed the 90% of probability in actual heating energy consumption in the whole apartment building in the district scale [16].

3.2 Polynomial models of interaction between floors

Figure 8 describes the goodness of fit in the polynomial models of interaction between floors. R-squared values are distributed between 0.60 and 0.85, while RMSE is dispersed between 12 and 20. As already found in the previous section 3.1, changing degrees of polynomial models does not result in the significant increase of the goodness of fit (Figure 8-(a)). The linear models indicate the good interpretation of unit-specific heating energy consumption. To improve the goodness of fit, two floors, the ground and the 12th floors, can be designed in second-degree models, as depicted by blue dots in Figure 8-(a) and (b).

Figure 9 shows that heating set-point temperatures on an upper floor are determined by changing heating set-point temperature in units where heating is on from 16 to 22°C. Although the heating set-point temperatures on the higher floors from the seventh to the top floor, except for the 8th floor, are the 90% of the probable range between 17 and 20°C, the lower floors from the ground to the eighth floors, except for the 7th floor, require higher heating set-point temperatures, above 20°C. Unlike the relation of heating controls in apartment units in inverse proportion (Figure 7), heating set-point temperatures between floors are in direct proportion (Figure 10). When higher heating energy use with the increase of heating set-point temperatures on an upper floor, heating energy consumption on the lower floor can expect to be reduced, because of heat transfer from the under-floor heating on the upper floor. To achieve the fixed target heating consumption, the heating set-point temperature in an apartment unit where heating is on is also increased with the set-point temperature increase on an upper floor.

The units from the ground to 6th and 8th floors show the possible range of heating set-point temperatures on an upper floor between 18.5 and 22.5°C in accordance with heating set-point temperature on an upper floor (Figure 10-(a)). The possible range among the 7th and 9th to top floors is between 17 and 21.5°C (Figure 10-(b)). This result shows that the temperature range between 17 and 20°C, which is defined as the 90% probability of heating set-point temperatures with the whole building approach, would underestimate heating energy use in apartment units on the lower floors (the ground- 6th and 8th floors), whereas it could be relatively accurate for the upper floors (the 7th and 9th – top floors).

4. Model demonstration

Through the model framework, new polynomial models optimised the heating controls of the individual apartment units to achieve the model estimations being more accurate towards the targeted/real heating energy consumption.

This section inputs the optimised dataset of heating controls into the previous simplified building simulation models, and examined the results, as shown in Figure 11. Figure 11-(a) depicts the recalculated heating estimation with the optimised heating controls in apartment units. With the polynomial models, the dataset of heating set-point temperatures was created when heating hours were from three to six hours. Figure 11-(b) describes the recalculated heating estimation with the optimised heating set-point temperatures between floors by applying heat set-point temperatures from 16^{o}C to 20^{o}C when seven hours heating.

At a glance, Figure 11-(a) and (b) inform more accurate heating estimation than the previous model estimation. Specifically, the best-fit model of heating controls in apartment units is the model with 5 hours of heating with the least value of CV RMSE, 5.8% (Table 2). Although the difference is not significant among the heating hours from three to seven hours, the model with eight hours heating demonstrates a higher difference from the targeted heating consumption (Table 2). Unlike the models with heating controls in units (Figure 11-(a)), the estimated heating energy consumption on an upper floor in Figure 11-(b) responds more sensitively depending on the change of heating set-point temperatures in units where heating is on. The best-fit model of heating set-point temperatures between floors is the model with 18^{o}C with the least value of CV RMSE, 5.6% (Table 2). The model with 19^{o}C may be more suitable for 6.7% although the level of CV RMSE is slightly higher.

5. Conclusions

High-rise apartment buildings have complicated conditions with high levels of uncertainties. Despite that, building energy modelling approaches have disregarded variations arising from the diversity of individual apartment units that have different locations exposed to different external environmental conditions and occupants independently controlling energy systems in each unit. This study focused on the variation of energy use arising from individual apartment units, and dedicated to developing an integrated approach to build the energy model with regard to the locations of apartment units and individual heating controls. This has been carried out integrating actual data into the existing building energy model, focusing on the physical conditions of individual units, in a building simulation, and then developing the new polynomial models with regard to the individual heating controls for further prediction.

The averaged heating energy consumption, 123.2 kWh/m^2/year, in apartment buildings constructed before 1980 were varied by the locations of apartment units from 96 to 171 kWh/m^2/year. The building simulation model was created by specifying the 15 individual apartment units placed in the different vertical locations. However, the model estimation revealed its vulnerability affected by the occupant-related factors. The new set of polynomial regression model was established and integrated to calibrate the inaccuracy of the simulation model estimation. Two building conditions of high-rise apartment buildings were used to create the polynomial regression models: heating controls in apartment units and heating set-point temperatures between floors. The set of polynomial model estimated the conditions of heating controls in order to consume the same amount of heating energy in the specific apartment units in the different locations.

With the set of the model interpreting heating controls in apartment units, it has been found that apartment units located in lower floors need either higher set-point temperatures up to 23ºC or longer heating hours (more than seven hours) than the probable range of heating controls for these apartment buildings (17 - 20ºC of heating set-point temperatures with three to six hours of heating).

With the set of the model for heating set-point temperature between floors, the lower floors from the ground to the eighth floors, except for the 7th floor, require higher heating set-point temperatures, above 20ºC although the heating set-point temperatures on the higher floors from the seventh to the top floor, except for the 8th floor, are the probable range.

In the most demonstration, the first building simulation model, regarding the physical conditions of the units in different locations, showed CV RMSE 23.8%. However, this disparity was significantly reduced to CV RMSE 5.8% with the model of heating controls in units and CV RMSE 5.6% with the model of heat set-point temperatures between floors.

Variation arising from individual apartment units may be disregarded if it is not a main consideration. Instead, some other aspects may be able to more significant than this issue. However, considering individual units has been proved to reduce the inherent uncertainties of estimating energy consumption in apartment buildings. This can be expected to bring about more accurate outcomes with building energy simulations.

Similar to this study, the variations in energy use in various other aspects have been considered in recent years, rather than using the average [30-32]. While for those considerations a number of models have been established using various methods [33-34], it is also useful to consider simplified mathematical approaches or empirical estimation methods, which will be the scope of further studies.

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