Validation of Bottom-up Type Residential Electricity Load Curve Simulation Model

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ABSTRACT

The authors have been developing a bottom-up type residential energy end-use simulation model, which simulates the residential electricity demand in 5-min increments. The purpose of this paper is to validate the model by using measured electricity consumption data. The model was validated according to the procedure for simulating cooling or heating energy consumption by using the measured electricity consumption data of room air conditioners (RACs) and occupants' presence schedule data which was extracted from measured data from distribution boards in 144 households. The model input was set according to a simulated result to validate, and the result was compared with the measured data in order to validate each step of simulation mentioned above. First, we validated heating or cooling load calculation and energy consumption simulation. As the results, this model underestimates heating load and electricity consumption in winter and overestimates the cooling load and the electricity consumption in summer. Then, we validated the determination of the RAC operational state. The results suggest that state transition probabilities determining the RAC on/off operational state should be reconsidered.

KEYWORDS

Residential electricity load curve, Heating and cooling energy consumption, Model validation

INTRODUCTION

In summer and winter, the electricity demands for cooling and heating, respectively, increases enormously, and the supply and demand balance within the power system in Japan becomes delicate. To maintain the balance while considering environmental impacts and economic efficiency, it is very important to cut the peak electricity loads by employing electricity-saving measures, such as photovoltaic (PV) power generation systems, demand responses, and related measures. Under these conditions, it is necessary to precisely simulate the electricity load curve on a power system scale with high-temporal resolution. We can do this by using a bottom-up type simulation model. The simulation can evaluate the effect of various electricity-saving measures to cut the peak load and predict the electricity load curve when various energy saving

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technologies are disseminated in the future. With the use of only measured data, however, it is difficult to make precise simulation and predictions.

In the residential sector, electricity demand is determined by the following procedure. First, the occupants' behavior is determined based on their lifestyles. Then, the appliances' on/off schedule is determined according to the occupants' behavior schedule. Finally, an energy demand profile is determined according to the appliances' on/off schedule and their electricity consumption. In addition, electricity consumption depends on various factors such as family composition, appliance ownership, occupants' lifestyle, weather conditions, and so on. Evaluating the effect of various electricity-saving measures on different households in detail requires the bottom-up type simulation model which has the capacity to determine the energy consumption by the same procedure as in an actual residence situation and to consider the diversity of households. However, it is difficult to validate the model systematically because the simulated results are affected by various factors in a complicated way.

Given the above background, the purpose of this paper is to validate the residential energy end-use model, which was developed by the authors (Shimoda et al. 2007). This is a bottom-up type model that simulates the electricity load curve on a power system scale with 5-min intervals. In this paper, the validity of the electricity demand for heating and cooling is verified by using measured room air conditioner (RAC) electricity consumption data and the occupants' presence schedule data.

METHODOLOGY

Outline of the residential energy end-use model

The residential energy end-use model simulates the residential energy consumption by the following procedure. First, the occupant's behavior schedule for each family member living in the simulated house is determined stochastically based on the Survey on Time Use and Leisure Activities (MIC 2006) in 5-min increments (Yamaguchi et al. 2014). Then, the operational state (on/off) of appliances is determined based on the occupant's behavior schedule. Next, the electricity consumption in a household is calculated based on the appliances' operation schedules.

This model considers a total of 912 household categories made up of 19 family compositions, 12 building categories (six categories for apartments and six categories for detached houses, which are set depending on the floor area), and four building insulation levels. The households in the region are classified into 912 categories based on the Population Census (MIC 2010) and insulation level percentages for residential building stocks. By adding up the electricity consumption amounts in each household, the residential electricity load curve on a power system scale is simulated.

The validity of the electricity demand in the Kansai region (a power system scale including 8.6 million households) in summer and autumn was verified using smart meter datasets in a previous study (Taniguchi et al. 2016). However, the validity of the electricity demand for each end-use had not been verified yet. In this paper, the validity of the electricity demand for heating and cooling was verified in order to simulate the energy consumption precisely in summer and winter, when cooling or heating appliances are operating.

Cooling and heating energy-use model

In Japan, RACs are commonly used for cooling in residential buildings. For heating, various kinds of appliances, such as RACs, electric heaters, gas heaters, and kerosene heaters, are used. This paper discusses only RACs for both cooling and heating. Energy efficiency of RACs changes every moment because it is determined based on the cooling or heating load. Therefore, it is more difficult to simulate the actual RAC electricity consumption compared to simulating other appliances. Our model simulates heating or cooling energy consumption in the following procedure, as shown in Figure 1Figure 1.

(1) The occupant's presence in the room is determined based on the occupants' behavior schedule.

(2) The natural air temperature of each room is calculated by a thermal circuit network method (Shimoda et al. 2007) that uses weather data, house plans, thermal specifications of walls and windows, air change rate and internal heat gain from human occupancy and appliances.

(3) The operational state (on/off) of an RAC is determined stochastically according to the room air temperature. Habara et al. (2004) measured the use of RACs in living rooms and bedrooms in order to examine the relation between room air temperature and RAC on/off operation. They derived RAC off-to-on state transition probabilities based on survey results and modeled the RAC on/off operation by applying the probabilities to a sigmoid function, as shown in Figure 2Figure 2.

(4) In the case that the RAC operation is on, the heating or cooling load is calculated according to the calculated natural room air temperature and the set air temperature by the thermal circuit network method stated in item (2).

(5) RAC electricity consumption is calculated based on the operation coefficient of performance (COP) of the RAC. In this model, the operation COP is estimated based on the outdoor air temperature, heating or cooling load, and the rated COP.

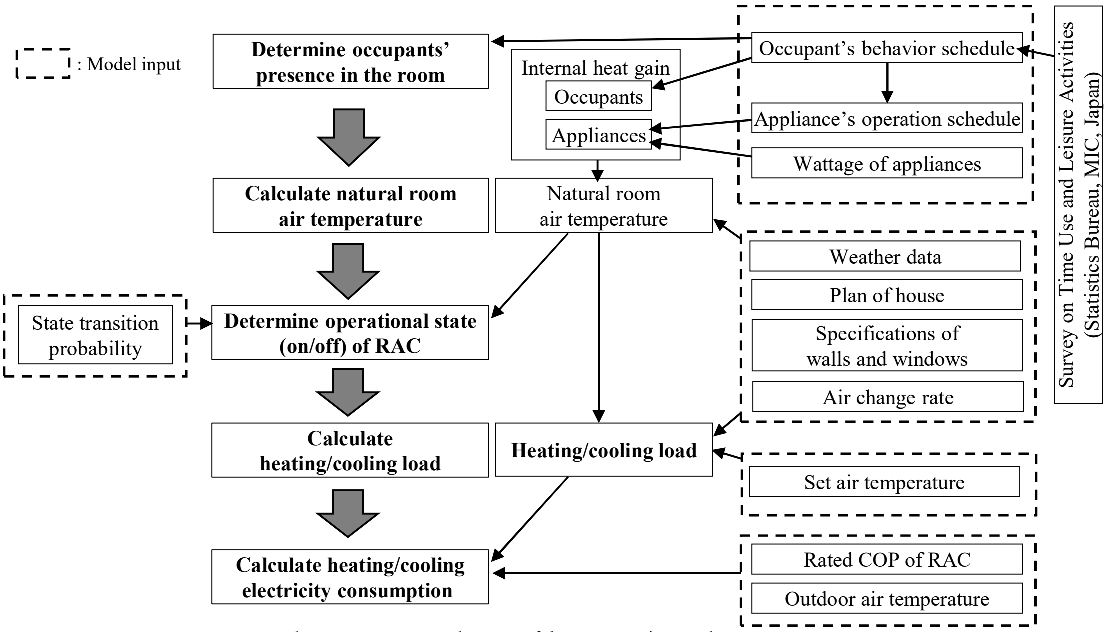

Figure 1. *Simulation procedure of heating/ cooling energy consumption*

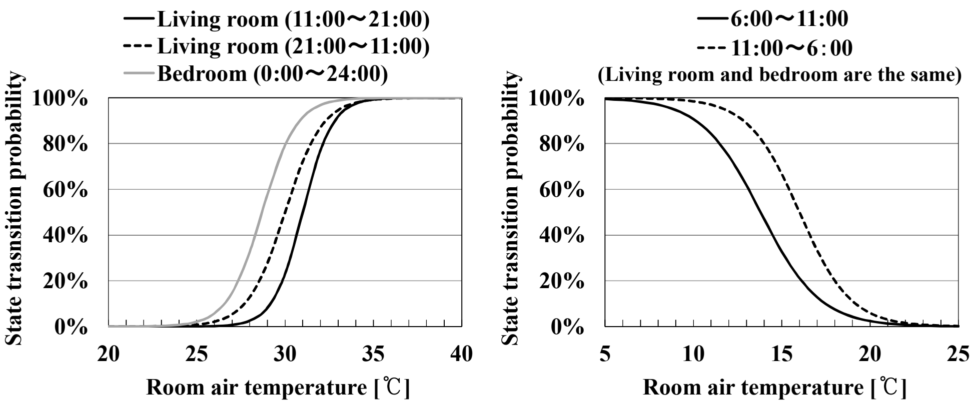

Figure 2. *State transition probabilities of RACs (left: cooling, right: heating)*

MODEL VALIDATION

Measured data

In this paper, the model was validated by comparing the simulation result with the measured data, RAC electricity consumption data and occupants' presence schedule data, which were extracted from measured data from the distribution boards of households. The measurement was conducted in 144 households in an apartment building in Settsu city, Osaka, Japan. This building was constructed in 2011. The time resolution of the data is 5 min and the measurement period is from January 1, 2012 to December 31, 2012. The information about construction type and age of the apartment building, examples of room layouts, and RAC specifications in the living rooms are available. The internal temperature was not measured.

From the measurement data, we can obtain the RAC operation status in each room and the building specifications of the sample households. Therefore, in this study, the model is validated under the same conditions as the measured data. Since the information of the family composition is not available, it was assumed that the sample households do not include single-person households by judging the information about room layouts. In addition, the distribution of family compositions in 144 households aligned with Settsu city based on the Population Census (MIC, 2010).

Validation flow

In this paper, the model input was set according to the simulation result to validate, and the result was compared with the measured data in each step of the simulation, as shown in *Figure 1*~~*Figure 1*~~. First, the heating or cooling load calculation and the energy consumption simulation (second, fourth and fifth steps in *Figure 1*~~*Figure 1*~~) were verified (Validation 1). Then, the determination of the RAC's operational state (third step in *Figure 1*~~*Figure 1*~~) was verified (Validation 2). Because the internal temperature was not measured, the natural room air temperature calculation (second step in *Figure 1*~~*Figure 1*~~) was verified in Validation 1. When each validation was conducted, the model input was set as follows.

Validation 1: The RAC's on/off operational state extracted from the measured RAC electricity consumption data was substituted for the state transition probabilities shown in *Figure 2*~~*Figure 2*~~. By comparing the simulated RAC electricity consumption with the measured data aligned with the RAC's on/off operation schedule, the heating and cooling load calculation and the electricity consumption simulation were verified.

Validation 2: When determining the occupants' behavior schedule, the presence schedule estimated from the measured data was substituted for the Survey on Time Use and Leisure Activities. The way to estimate the occupants' presence schedule from the measured electricity consumption data from the distribution boards of households was proposed by Hamada et al. (2016). In this case, the RAC's on/off operational state was normally determined stochastically based on the state transition probabilities shown in *Figure 2*~~*Figure 2*~~. By comparing the simulated RAC's on/off operation state with the measured data while aligning the occupants' presence schedule with the measured data, the determination of the RAC's on/off operational state was verified.

Simulation results

(1) Validation of heating or cooling load calculation and electricity consumption simulation (Validation 1)

Figure 3~~*Figure 3*~~ and *Figure 4*~~*Figure 4*~~ shows simulated and measured RAC electricity consumption averaged for the weekdays in January and August. As shown on the right side of *Figure 3*~~*Figure 3*~~, the simulation result of the bedrooms in January agrees well with the measured data. However, as shown on the left side of *Figure 3*~~*Figure 3*~~, the simulation result of the living rooms in January is 40 to 50 W per household lower than the measured data in the morning and the evening. This may be because this model does not consider households located in the corner and at the top or bottom floor of apartment buildings. In addition, when calculating the natural room air temperature and the heating or cooling load in an apartment building, it is assumed that heat does not go in and out neighbor households. Therefore, this model does not consider escaping of heat in the room when the neighbor household is vacant. As a result, this model may underestimate the amount of heat going out of the rooms and overestimate the room air temperature in winter.

As shown on the left side of *Figure 4~~Figure 4~~*, the simulation result of the living rooms in August is 20 to 50 W per household higher than the measured data from approximately 12:00 to 6:00. In addition, as shown on the right side of *Figure 4~~Figure 4~~*, the simulation results of the bedrooms in August are slightly higher than the measured data from nighttime to early morning. This may be because the simulation does not consider opening the windows or using electric fans when the occupants are not using their RACs. In this model, the air change rate is constantly 0.5 times/hour when the natural air temperature and the heating or cooling load are calculated. As a result, this model may underestimate the amount of outside air entering the rooms and overestimate the room air temperature in summer.

The results suggest that this model underestimates the heating load and electricity consumption in winter, and overestimates the cooling load and electricity consumption in summer. Therefore, this model may need to consider households located in the corner and at the top or bottom floor in the apartment buildings, and the case that the neighbor household is vacant. In addition, opening windows and using electric fans may need to be considered.

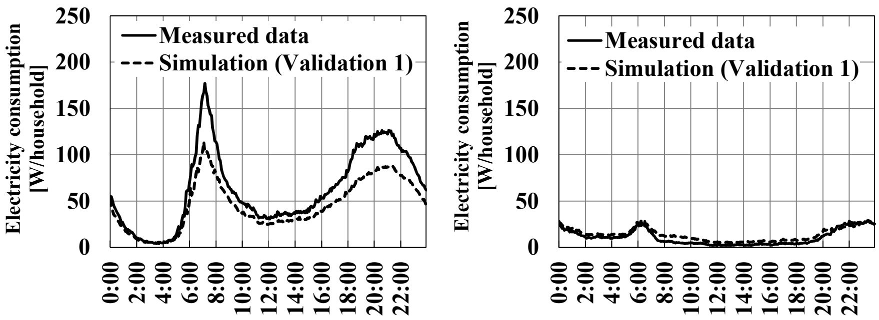

Figure 3. *Simulated and measured RAC electricity consumption on weekdays in January (left: living room, right: bedroom)*

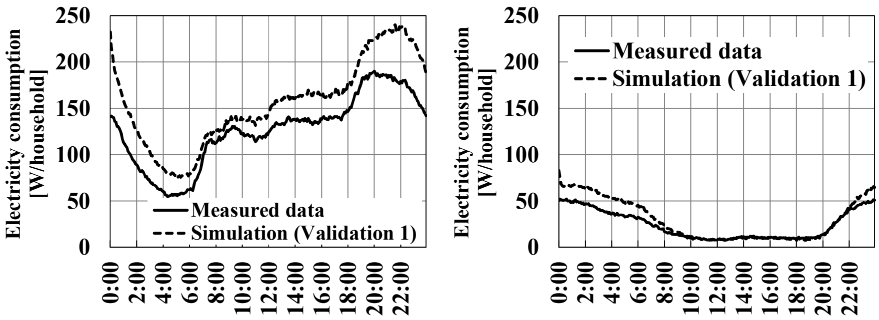

Figure 4. *Simulated and measured RAC electricity consumption on weekdays in August (left: living room, right: bedroom)*

(2) Validation of the RAC operational state (Validation 2)

Figure 5~~Figure 5~~ and *Figure 6~~Figure 6~~* shows the simulated and measured RAC operation rates averaged for weekdays of January and August. The RAC operation rate is defined as the proportion of the number the households using their RACs to the total number of households. As shown in the left side of *Figure 5*~~*Figure 5*~~, the simulation results of the living rooms in January are lower than the measured data by 15 to 25 % in the morning and evening. This may be because the model overestimate the room air temperature, as the result of *Figure 3*~~*Figure 3*~~ suggested. By judging the large gap between the simulation result and the measured data, the reason also may be that the transition probability in the model underestimates the RAC operation rate.

As shown on the right side of *Figure 6*~~*Figure 6*~~, the simulation result of the bedrooms in August agrees well with the measured data. However, as shown on the left side of *Figure 6*~~*Figure 6*~~, a constant gap exists between the simulation result of the living rooms in August and the measured data. Even though the result of *Figure 4*~~*Figure 4*~~ suggested that the model may overestimate the room air temperature in summer, the simulated RAC operation rate is much lower than the measured data. One possible reason is that in the sample households, occupants could always be using RAC independent of the room air temperature in the middle of summer.

The results suggest that this model underestimates the RAC operation rate in the living rooms in winter and summer. Therefore, the state transition probabilities determining the RAC on/off operational state may need to be reconsidered.

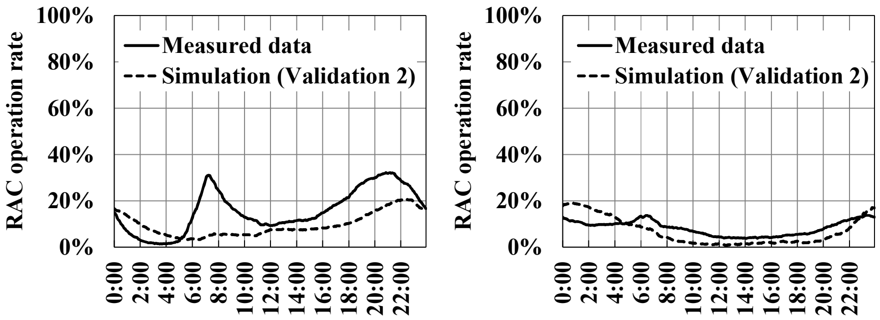

Figure 5. *Simulated and measured RAC operation rates on weekdays in January (left: living room, right: bedroom)*

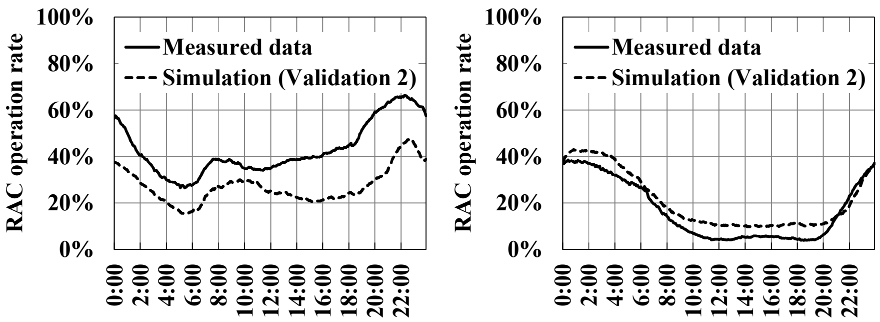

Figure 6. *Simulated and measured RAC operation rates on weekdays in August (left: living room, right: bedroom)*

CONCLUSION AND IMPLICATIONS

This paper proposed an approach for verifying the validity of the electricity demand for cooling and heating with the use of the measured electricity consumption data according to the procedure for simulating cooling or heating electricity consumption. The residential energy end-use model developed by the authors was validated.

The simulated RAC electricity consumption (Validation 1) of the living rooms in the winter in the morning and evening was 40 to 50 W per household lower than the measured data. The target apartment building in this study has 18 floors, so about 10 % of the sample households are located at the top or bottom floor. There are also some cases that the sample households located in the corner of the building or the neighbor household is vacant. Consideration of these households can improve the simulation result underestimating the amount of heat going out of the rooms and can avoid overestimating the room air temperature. In addition, the simulated RAC electricity consumption (Validation 1) in the summer was 20 to 50 W per household higher than the measured data. When calculating the cooling load, a simulation especially in the house whose insulation level is high, such as the target apartment building in this study, should consider opened windows and the use of electric fans. Consideration of them can improve the simulation result underestimating the amount of outside air entering the rooms and can avoid overestimating the room air temperature.

The simulated RAC operation rate (Validation 2) of the living rooms in winter in the morning and evening was 15 to 20 % lower than the measured data. In addition, the simulated result of the living rooms in summer was 10 to 20 % lower than the measured data. These results suggest that when determining the RAC's on/off operational state, the simulation should consider not only the room air temperature but also the possibility of using RAC independent of the room air temperature in the middle of summer. In the sample households, over 90 % of the occupants was always be using RAC independent of the room air temperature when they were in their rooms in the middle of summer.

As further work, we will reconsider the amount of heat entering and going out the rooms in apartment buildings and examine the effect of ventilation and electric fans on the electricity load curve. In order to apply the model on a city or power system scale, we will also investigate the actual situation of the occupants' operational state of RACs for many more sample households as a target to improve the state transition probability. This is because the 144 sample households are biased in terms of properties such as building types, heat insulation properties, occupants' lifestyles and so on. The RAC's on/off operational state may be affected by the properties of the sample households. In addition, other heating appliances such as electric heaters should be considered, because this paper discussed only RACs.

To validate heating and cooling electricity consumption in the proposed procedure, not only measured electricity consumption data but also information of occupants' presence schedule, building specifications and RAC specifications are needed. In addition, measuring room air temperature and information of heating appliances other than RACs are required for further validation.

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