Validation of an Energy Demand Model of Residential Buildings

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ABSTRACT
This paper presents a validation of an energy demand model of residential buildings. This model quantifies electricity and city gas demand of a house in the 5-min resolution as the sum of consumptions by all home appliances used in the simulated house. In the model, time allocation of household members in a day is first stochastically simulated. This time allocation data is then converted to the operation of home appliances and equipment. For this conversion, a probability showing how frequently considered appliances and equipment is operated when a behavior is undertaken is given as an input data. By using this probability, the operation of appliances is randomly determined. Finally, energy consumption of each appliance and equipment is determined by considering specification of the appliances. After explaining the simulation model, we validated the model by comparing simulation result with electricity demand measured from 227 households.

KEYWORDS
Residential energy demand, Time use, Bottom-up modelling approach

INTRODUCTION
Usually, in a household energy demand model, the occupant behavior is given by a pattern that represents an average occupant’s behavior. Although this approach is easy to set up and useful to estimate the total energy demand of households or the average pattern of energy consumption, it does not provide useful inputs to replicate a high-temporal resolution energy demand with a realistic time-varying characteristic and a variety among households. To replicate such energy demand, stochastic occupant behavior must be directly simulated.

This paper presents an energy demand model of residential buildings combining a stochastic model of behavior of household members. This model quantifies energy demand of a house (e.g. electricity and city gas) in the 5-min resolution as the sum of consumptions by all home appliances operated by household members in the simulated house. We validate this model in the paper by using a measured electricity consumption data collected from approximately 227 households living in an apartment building. In order to reflect the variety in energy demand among households, the model gives different conditions to each simulated household.

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for family composition, time allocation of people, ownership and specification of home appliances. This paper first presents the simulation procedure of the model. Then, the model is validated by comparing simulation result with electricity demand collected from 227 households. We finally discuss the weaknesses in the input data and modelling approach of the model.

ENERGY DEMAND MODEL OF RESIDENTIAL BUILDINGS

Data preparation for simulation

Figure 1 shows the procedure of the simulation model. The first step of simulation is to define specification of house and family members of simulated households. The model contains databases on house specification and family composition. The family composition is defined by a combination of family members with attributes distinguished by age, gender and occupation as listed in Table 1. There are 6 and 9 house specifications for detached and apartment houses classified by the size of house. For each house specification, a house archetype is prepared. The archetypes have specific conditions on size, shape, floor plan, and other physical conditions of house like insulation performance, which is necessary to conduct a thermal simulation to estimate energy consumption for space heating and cooling.

Second, the ownership and specification of home appliances are given to simulated house. For this process, we use frequency distributions on these data. The frequency distributions were developed based on a questionnaire survey that collected information from approximately 800 households living in Osaka, Japan. By giving a random number to a frequency distribution, a condition for each appliance is randomly determined. For example, by giving a random number, a number of TV used in a house is selected. Then, the size of TV is selected by giving a random number to the corresponding frequency distribution. Finally, specification of electricity consumption of selected TV is determined using a frequency distribution on electricity consumption of TV stock with a variety of TV size.

After selecting appliances used in a house, a room is selected in which each appliance is placed. If two TV is owned in a simulated household, one TV is placed in the living room and the other TV is placed in a private room of a children.

<table>
<thead>
<tr>
<th>Table 1. Family composition and house archetype</th>
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<tbody>
<tr>
<td>Family composition</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>3 people</td>
</tr>
<tr>
<td>5 people</td>
</tr>
<tr>
<td>6 people</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>
Stochastic simulation of time allocation of household members

In the previous step, attributes of household members were defined. According to the attributes, time use data, the input data to generate time allocation of household members, is prepared. Time use data contains statistical information on time allocation for 85 kinds of behaviors on weekdays and holidays. In this model, the behaviours are divided into routine and non-routine behaviours. Routine behaviours are those undertaken routinely every day, which are sleeping, outing for work or school, eating, and bathing. These routine behaviors are placed on a day prior to the rest of behaviors, non-routine behaviors. The duration of routine behaviours is first determined based on a statistical distribution of the duration. Then these duration, which is called discrete behaviours, are placed on timeline of day by using probability distribution of time allocation of these routine behaviours. After placing all the routine behaviors, the gaps between the routine behaviours are filled by non-routine behaviours. For this filling gap process, two kinds of data are used. The first data is transition probability from a behaviour to another behaviours. After a routine behaviour is ended, a random number is given to the transition probability to determine the behaviour after the routine behaviour. Then, by using the second data, statistical distribution of the duration of non-routine behaviours, the duration of the selected non-routine behaviour is determined. This process is repeated until all the gaps are fulfilled.

There are several statistical data used in the model. These data are all developed for each of occupants attribute category based on the result of Japanese national time use survey. A detail explanation on the model and database development is given elsewhere (Yamaguchi et al. 2014)
Conversion from time allocation to energy consumption of home appliances

This time allocation data is then converted to the operation of home appliances (Higashino et al. 2014). For this conversion, a probability showing how frequently considered appliances and equipment is operated when a behavior is undertaken is given as an input data. By using this probability, the operation of appliances is randomly determined. Finally, energy consumption of each appliance is determined by considering specification of the appliances.

Based on the time allocation result, the room in which occupants spend time is also determined based on an input file defining the relationship between behavior and room. This room use information is used to determine the operation of space lighting, heating and cooling. For rooms in which occupants spend time, the necessity of operation is judged based on the result of indoor condition. For lighting, illuminance at a reference point in rooms is simulated and compared with a reference value. If the natural illuminance is higher than the reference value, the lighting is judged to be off. For space heating and cooling, similar judgment is conducted. Thermal load and natural room air temperature is first calculated by a thermal circuit model utilizing house archetype data, internal heat gain and meteorological data. Internal heat gain is calculated by using energy consumption of home appliances and lighting. If natural room air temperature is out of pre-defined comfort range in room air temperature, it is assumed that air-conditioner or heating devices are operated. To calculate energy consumption of air-conditioner, a regression model of coefficient of performance (COP) is used that takes into account the influence of part load ratio and indoor and outdoor conditions.

The model also calculate energy consumption for water heating. First, an amount of hot water is determined for each time step based on household members’ time allocation data. Time allocations that accompanies hot water use are as follows: bathing, showering, face washing, cooking and dish washing. The quantity consumed for each of these behavior is given randomly to each household in the data preparation process by using a database. The database was developed based on measurement of consumption of city gas, water and electricity collected from approximately 200 households so that a variety in water quantity was reflected in the database. The methodology to determine hot water quantity from the consumptions of city gas, water and electricity is given elsewhere (Ukawa et al. 2014).

VALIDATION METHODOLOGY

Data used for validation

For validating the developed model, we used electricity consumption measured at each circuit of distribution boards installed in 227 houses in a multi-family building located in Osaka, Japan. The time resolution of the measurement is 1 minutes. We compare the mean and standard deviation of electricity demand calculated by the simulation model with those of measured data.

The electric distribution board has a dedicated circuit for air-conditioner,
refrigerator, cloth washer, microwave and dish washer. The other circuits are to deliver electricity to lighting and plug load in a room or a group of rooms. For the appliances with their dedicated circuit, electricity consumption is directly compared. For the other appliances, total consumption is compared.

**House archetype and family composition**

We simulate electricity demand of 350 households for validating the developed model. Table 2 shows house archetype and family composition given to the model. For the other conditions, as mentioned earlier, a condition is randomly selected by using databases on frequency distribution of these conditions.

<table>
<thead>
<tr>
<th>Family compositions</th>
<th>2L DK 55 m²</th>
<th>3L DK 70 m²</th>
<th>4L DK 80 m²</th>
<th>Family compositions</th>
<th>2L DK 55 m²</th>
<th>3L DK 70 m²</th>
<th>4L DK 80 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working couple</td>
<td>1 19 7</td>
<td>7 Working female &amp; 2 children</td>
<td>0 7 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Couple</td>
<td>1 19 7</td>
<td>Female &amp; 2 children</td>
<td>0 8 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working female and child</td>
<td>1 13 4</td>
<td>Working couple &amp; 2 children</td>
<td>1 33 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mother and child</td>
<td>1 17 6</td>
<td>Working male, housewife &amp; 2 children</td>
<td>2 41 17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working couple and child</td>
<td>2 30 11</td>
<td>Working couple &amp; 3 children</td>
<td>0 9 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working male, housewife</td>
<td>2 38 14</td>
<td>Working male, housewife &amp; 3 children</td>
<td>0 11 5</td>
<td></td>
<td></td>
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</tbody>
</table>

**RESULT**

**Total electricity demand**

Figure 2 shows the mean electricity demand of two representative days, May 13 and 14. On these days, most households do not use air-conditioner. The red line shows simulation result while the black line shows measured demand that is the sum of electricity consumptions measured at all of the electric circuits. As shown in the figure, there are four features in the simulation model.

First, simulation model has higher peak in the morning from 6h00 to 9h00 than the measured demand on weekdays (May 14), though the timing of peak agreed well. This result indicated that although the simulation result of time allocation is appropriate, operation of home appliance is not appropriate. This point is discussed later. Second, the peak in the morning on May 13, the representative day of holidays, is different between the simulated and measured demand. This result indicates that time use data inputted to the model for holidays is not appropriate. Third, the simulated demand during night is smaller than measured demand. This discrepancy mainly caused from the model of time allocation of household members. This point is also discussed later.

The fourth feature is about distribution of electricity demand among households. Figure 2 also shows the upper and lower quartile points among households. Pink range shows those of simulation result, while ash range shows those of the measured demand. As shown in the figure, the distribution among households in the simulated electricity demand is smaller than the measured demand, especially over holidays. This can be attributed to the sampling process of input data. In this study, we assumed that occupants have same time use
characteristics if the occupants’ attribute is same. Additionally, the parameters determining the ownership and the operation of home appliances were randomly given. However, these parameters could have a relationship that makes households with high and low energy demand.

![Figure 2. Mean total electricity demand per household](image)

**Composition of electricity demand**

Figure 3 shows the mean consumption of appliances with dedicated circuit for measured consumption. As shown in the figures, the consumption of refrigerator and consumption on weekdays except microwave agreed well. The simulation result on holidays are smaller than measured. For microwave, the operation is more frequently occurred in the reality. Figure 4 shows sum of electricity consumption of appliances placed in kitchen. The black line shows the measured consumption in kitchen including plug load and lighting load. As lighting load is included in the measured consumption, we cannot directly compare the simulation result and measured consumption. However, the peak in the morning observed in the simulation result is too large compared to the measured consumption.

Finally, Figure 5 shows the sum of electricity consumption of the other appliances. The figure on the top shows the simulation result with composition by appliances. The figure on the bottom shows the measured consumption classified by rooms. As mentioned earlier, electricity demand from 6h00 to 9h00 in the simulation result is larger than the measured. The figure shows that the consumption of lighting, and hair dryer, at least, too large. This can be attributed to the setting of operation of appliances. More importantly, lighting consumption in the simulation result increased around 18h00. This is because the model calculated indoor illuminance to determine the necessity of turning on room light by using common parameters among households. This parameter must be given to reflect the realistic distribution of the parameters to replicate realistic energy demand.

Additionally, decrease in electricity consumption after night peak around 20h00 is earlier in the simulated consumption than the measured consumption. This can be mainly attributed to the discrepancy in the time use data used in the model of
CONCLUSION AND IMPLICATIONS

This paper presented an energy demand model of residential buildings. This model quantifies electricity and city gas demand of a house in the 5-min resolution as the sum of consumptions of all home appliances driven by stochastically simulated behavior of household members in the simulated house. This model was validated by comparing simulation result of electricity demand with those measured from 227 households. The
validation revealed the model has the following weaknesses; 1) The time use data, used for generating the daily behavior of household members, for holidays and for night is not appropriate, as morning peak in electricity demand on holidays occurred too early and decrease in electricity consumption after night peak around 20h00 to early morning is too fast; 2) Appliances for cooking and household maintenance as well as lighting are operated too frequently from 6h00 to 9h00 due to the conversion model from occupants daily behavior to appliances’ operation; 3) Method to give parameters for households must be established to reflect realistic distribution in electricity demand among households.

**Figure 5.** Mean electricity consumption for the remaining lighting and appliances

**ACKNOWLEDGEMENT**

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**REFERENCES**


