Bottom-Up Simulation Model for Estimating End-Use Energy Demand Profiles in Residential Houses

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ABSTRACT

A bottom-up simulation model for residential house is developed and described in this paper. The model simulates the usage of domestic appliances probabilistically over time in terms of consumed energy, based on the activities of the people in the house; for example, a microwave oven is likely to be used during cooking activity. The inputs to the model include structure of households to be simulated, activity of household members, profiles of electric appliances and probability of appliance usage.

Actual end-use load curves for over 50 residential houses have been obtained from a monitoring project that was carried out by the authors from Oct. 1998 to March 2002 in a newly developed residential town near the cities of Kyoto and Nara. The validity of the developed model has been tested by comparing the electric power consumption curves obtained from the model with the measured ones. It had been shown that the model can reproduce the end-use energy demand profile well.

Introduction

End-use energy demand profile is of vital importance for understanding energy problems in buildings. A number of monitoring projects have been carried out in different countries, however, measurement of the load curves for each end-use purpose for an extended period of time is costly and time consuming. Hence, it would be better if we could develop a computer simulation model from which the actual demand curves can be generated with some accuracy. The so-called bottom-up simulation models [Capasso 1994, Michalik 1997a, 1997b, Tsuji 1997] relate the activities of people in a building to the use of energy and therefore construction of these models would help us understand the structure of energy demand more precisely.

In this paper, a bottom-up simulation model for a residential house developed by the authors will be described. In the model, household members are categorized by the profile of daily life, e.g., people with jobs, children, etc. and appliances are represented by such attributes as unit power consumption, stand by, duration of operation, associated activity, etc. An activity of the member such as watching TV will be related to the use of appliances.

The output of the developed model is compared with the actual end-use energy demand profiles that have been obtained from a monitoring project that the authors have carried out in which a total of 66 residential detached houses were monitored for the period of one to two years. Although there are some differences, it will be shown that the simulation model can regenerate the end-use energy demand profile well.

Development of the Bottom-Up Simulation Model

Basic Concept

The basic idea of the developed model is taken from the paper by Capasso [Capasso, 1994] and modified by the author [Tsuji, 1997]. The model essentially follows the usage of electric appliances in a residential house over the times of a day. Many of the appliances are used by one of the members of the household, hence it is necessary first to simulate the activities of the members of the house in order to simulate the related usage of appliances. If this is successfully done, then the energy consumption by the time of the day can be calculated by summing up all the appliances under consideration in the house. By repeating this calculation for different days and for different households, the energy consumption in the domestic sector can be generated. The approach taken here is similar to the one described in the papers by Michalik [Michalik 1997a, 1997b]. The major difference is the method of relating the activity of a household member to the use of appliances. Michalik proposed an approach in which a combination of what he calls "life-style matrix" and "possibility of use" that essentially translates linguistic variables into parameters in his model by means of fuzzy filters, is used in order to simulate the use of appliances. In this paper, classical "probability of use" is used, however it is considered as unknown parameter that is to be identified by utilizing the monitored data, as this will be explained in a later section.

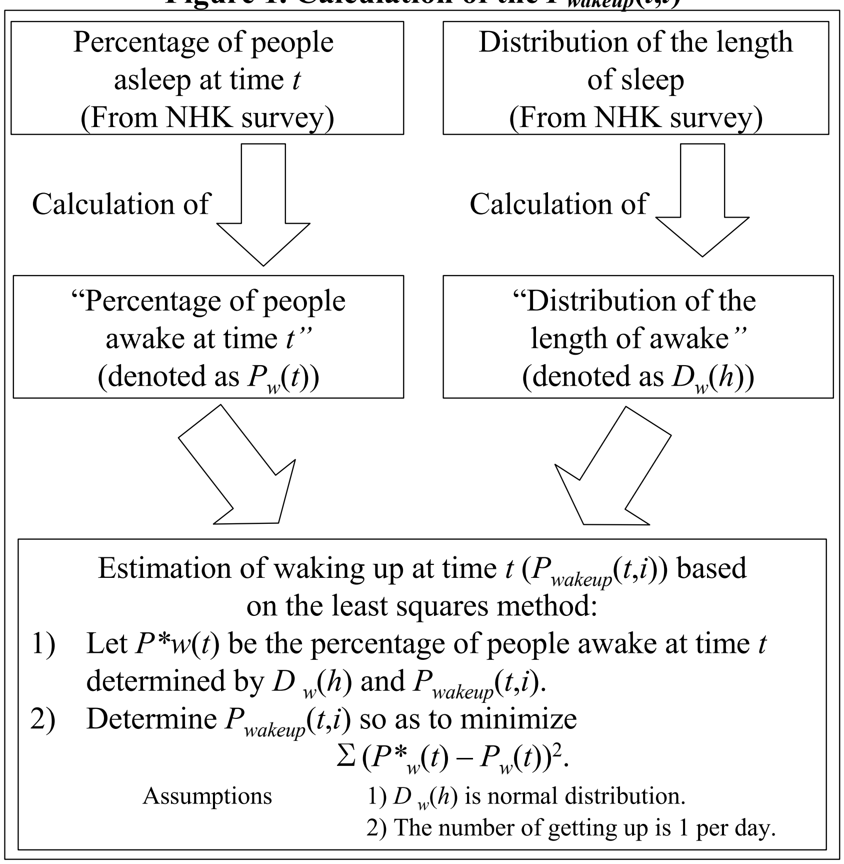
Categorization and Time Schedule of Household Members

The behavior of a household member depends on the category to which the member belongs. The Nippon Broadcasting Association takes a nation wide survey every 5 years on the activities of people, and the various questions in this survey will provide us with the basic information needed here [NHK 1990]. In this NHK survey, the household members are categorized into 5 groups, i.e., people with jobs, female at home, children (in elementary school, junior and senior high school), college students and elderly people (over 60 years old). The developed model uses this categorization. By designating the number of people in each of these categories, it is possible to represent different structures of households.

Next, a method for generating the daily time schedule of a household member is described in detail. The activities of the people in the house can be divided into two classes; one of which is related to whether they are at home and awake, and the other is the categorized activities directly relevant to the usage of domestic appliances (e.g., cooking, cleaning, watching TV, etc.). In order to determine whether a person in a specific category i is in the house and awake, the probability that a person wakes up at time τ (denoted as $P_{wakeup}(\tau,i)$) and the probability that a person goes out at time τ (denoted as $P_{out}(\tau,i)$) are used. These probabilities can be obtained by distributing questionnaires to households, but if this data is not available, then these probabilities must be estimated. In this model, $P_{wakeup}(\tau,i)$ is estimated for each category i by utilizing the following two sets of data from the NHK survey, i.e., "the percentage of people asleep at time segment t in a day", and "the distribution of the length of sleep". From these two sets of data, it is possible to calculate "the percentage of people awake at time segment t in a day", and "the distribution of the length of awake". By assigning a certain temporary value for $P_{wakeup}(\tau,i)$ and by using "the distribution of the length of awake", it is possible to simulate the state of whether the people are awake at time segment t or not and hence the value of "the percentage of people asleep at time segment t in a day" corresponding to the temporary value of $P_{wakeup}(\tau,i)$ can be calculated and compared with the data of "the percentage of people asleep at time segment t in a day". The unknown probability $P_{wakeup}(\tau,i)$ can then be determined in such a way that the difference between the calculated value and the actual value from the survey is minimized in the sense of least squares. Note that the length of time segment considered here is 15 minutes. Figure 1 shows the flowchart of these calculations.

For the estimation of $P_{out}(\tau,i)$, the data of "the percentage of people at home at time segment t in a day", and of "the distribution of the length of staying at home" that are available from the NHK survey can be used in the similar way as above.

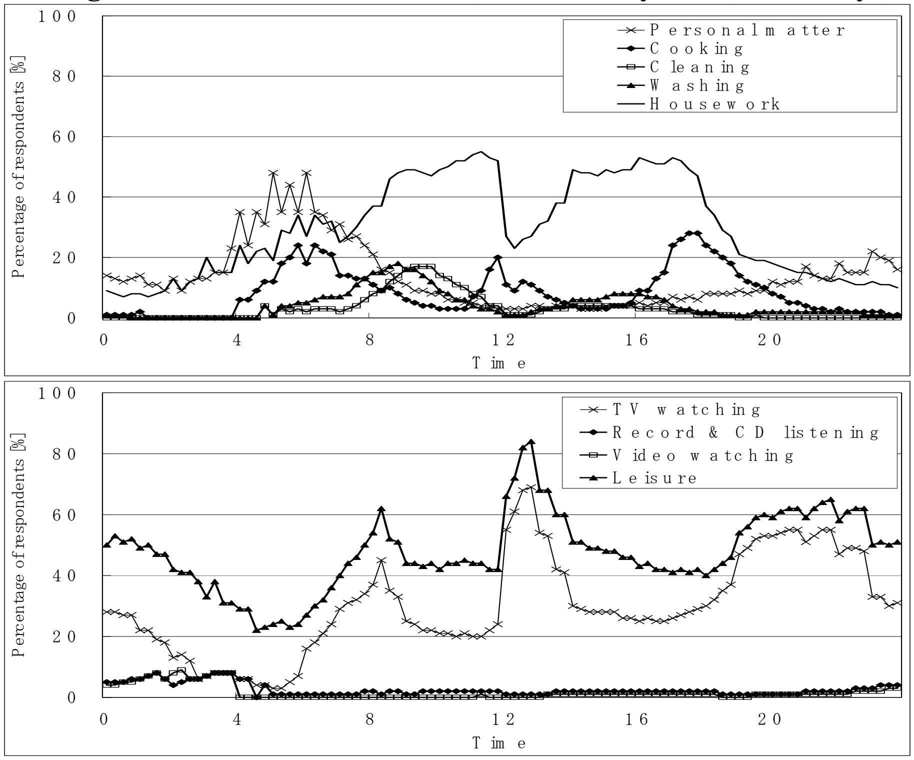
Figure 1. Calculation of the $P_{wakeup}(t,i)$



The activity other than sleeping and going out is initiated by using the probability of performing one of the categorized activities k at time segment t based on the member people at home and awake (denoted by $P_{activity}(t,k)$). This probability is equivalent to "the percentage of people performing one of the categorized activities at time segment t" that is available also from the NHK survey (see Fig.2).

In summary, the daily schedule of a person in a house is generated according to the three kinds of probability, i.e., $P_{awake}(\tau,i)$, $P_{out}(\tau,i)$ and $P_{activity}(t,k)$.

Figure 2. Profiles of Activities of Household Members (Percentage of People Performing One of the Categorized Activities At Time T; Nhk Survey 1990, Weekdays, All Japan)



Representation of Domestic Appliances

There are many domestic appliances in a residential house. In the developed model, the appliances are represented by the following set of attributes.

1. Categorized activity (At home and awake, Cooking, Cleaning, Personal matter, Washing, Watching TV, Listening Record & CD, Watching Video, Contacting Mass Media and Sleeping): The activity of a household member is related to the usage of an appliance and this categorization is also adopted from the NHK survey.
2. Operational mode (Automatic, Semi-automatic, Manual): Automatic means that the use of the appliance is independent of the activity of the household member (e.g., refrigerator). Semi-automatic means that the appliance is turned on by the household member but it is turned off automatically (e.g., automatic washer). Manual means that the appliance is turned on and off by the household member and hence the member is occupied by the appliance (e.g., vacuum cleaner).
3. Duration of operation (Minutes)(Minimum value, Maximum value): Typical duration between minimum and maximum values is assigned for each appliance.
4. Unit power consumption (W) (Minimum value, Maximum value): Typical unit consumption between minimum and maximum values is assigned for each appliance.
5. Standby power consumption (W)(Minimum value, Maximum value): Typical consumption is assigned.
6. Limit on repeated usage: This is for excluding excessive number of times of using the same appliance. For example, a rice cooker is unlikely to be used 10 times per day.

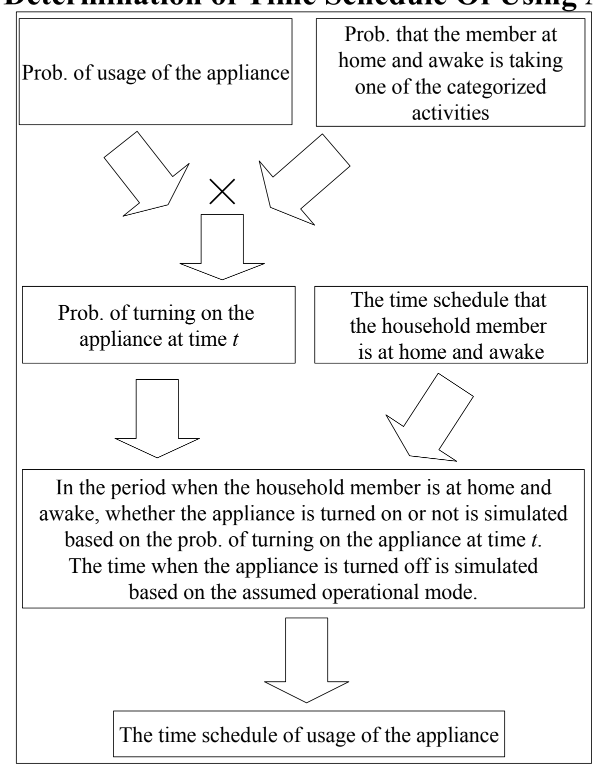
7. Saturation rate: This is not directly related to the activation of an appliance but this is used when it has not been determined if a certain appliance is present in a given household or not.

Operation of Temperature Independent Appliances

In order to activate one of the appliances under consideration, the probability of usage is used. Probability of usage is defined by the probability of using an appliance j conditional on performing one of the categorized activities k (denoted by $P_{usage}(j/k)$). By using this probability, an appliance is turned on according to the probability of activation which is calculated by $P_{usage}(j/k)*P_{activity}(t,k)$.

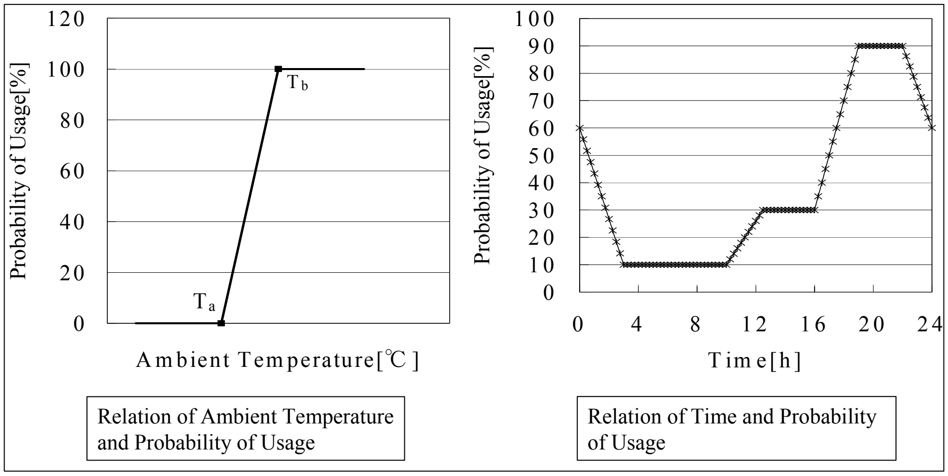
$P_{usage}(j/k)$ is considered as a set of parameters for which no appropriate statistical data is available. From a different point of view, $P_{usage}(j/k)$ is also considered a set of adjustable parameters and plays a key role in the model. If a set of measured data is available, $P_{usage}(j/k)$ can be tuned properly even taking the possibility of its dependency on the time of a day into account. This will be described more in detail in a later section. Once an appliance is turned on, it is operated according to the operational mode defined in the previous section. The determination of time schedule of using appliances is illustrated in Fig.3.

Figure 3. Determination of Time Schedule Of Using Appliances



Space cooling appliances. The use of air-conditioners for space cooling depends naturally on the ambient and room temperatures. The energy necessary or used for space cooling can be calculated if the various relevant data of a residential building and an appropriate simulation program that can calculate thermal load of residential houses are available. However, these calculations are often time consuming and their accuracy is not always guaranteed when the house is used in actual environmental condition. Here, a very simple way of modeling of the use of air-conditioners is adopted as shown in Fig.4. It is assumed that the $P_{usage}(j/k)$ defined in the previous section depends also on the ambient temperature and is modified by designating the temperature Ta in Fig.4 when persons in the house start thinking about using air-conditioners and the other temperature Tb when the persons definitely use air-conditioners.

Figure 4. Modifying $P_{usage}(j/k)$ for Air-Conditioners for Cooling



In the developed model, only an air-conditioner in living room is considered for simulation. It is assumed that the air-conditioner can be turned on only when at least one of the household members are at home and awake, and it is treated as semi-automatic with constant energy consumption per unit of time duration, i.e., possible transients in energy consumption are not treated in this model.

Space heating appliances. There are a number of alternative methods for space heating. Since the space heating appliances are used mainly in the living room of residential houses in Japan, the model considers those appliances as air-conditioner (in heat pump mode), electric fan heater, electric resistive heater, kotatsu (a table with small electric heater) and electrically heated carpet. A heat pump can be used both for space cooling and heating purposes, therefore it is treated as different appliance for each purpose. The method to activate each appliance is similar to the one described for space cooling appliances as shown in Fig.5. That is, we assume that the $P_{usage}(j/k)$ is modified by designating the temperature Td in Fig.5 when persons in the house start thinking about the use of an space heating appliance and the other temperature Tc when the persons definitely use the space heating appliances. The possible rise in room temperature by the use of a space heating appliance is not modeled; instead, the use of a space heating appliance is determined at every time segment (15 minutes) and energy consumption over 15 minutes is assumed to be constant.

Refrigerators. Energy consumption of refrigerators depends naturally on room temperature and this must be taken into account in the model. As it will be described in a later section, the authors carried out extensive monitoring of energy consumption in residential houses. It was found from the results of this monitoring that there is a strong correlation between ambient temperature and the demand ratio (the ratio of one day power consumption over annual consumption) as shown in

Fig.6. Therefore, if annual consumption is assumed, then the level of power consumption over a day can be determined by the averaged ambient temperature of the day.

Figure 5. Modifying $P_{usage}(j/k)$ for Electric Heater

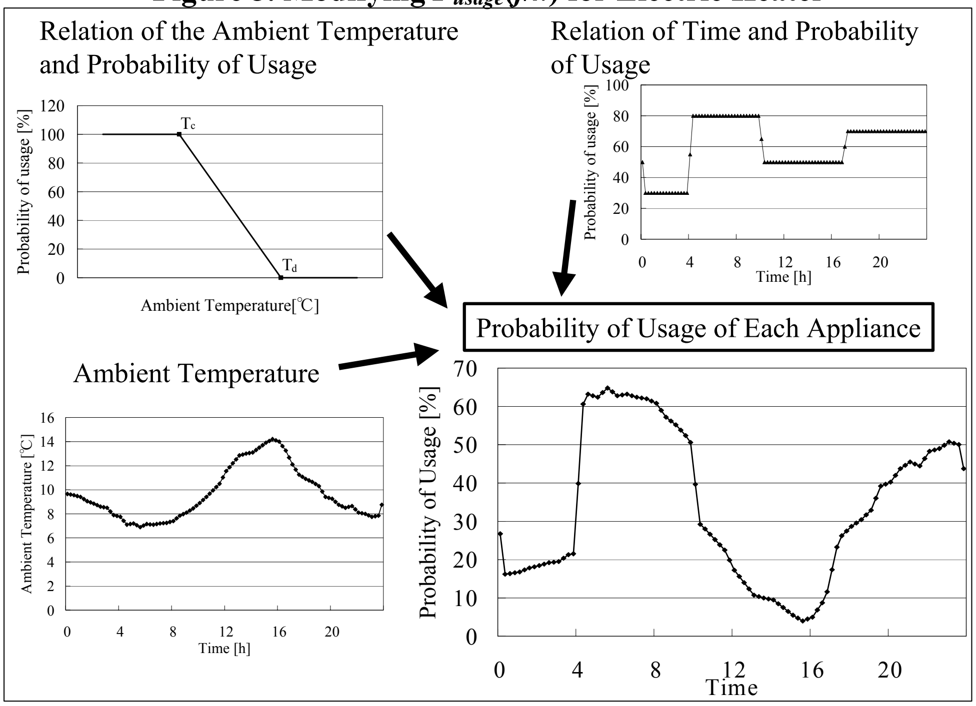
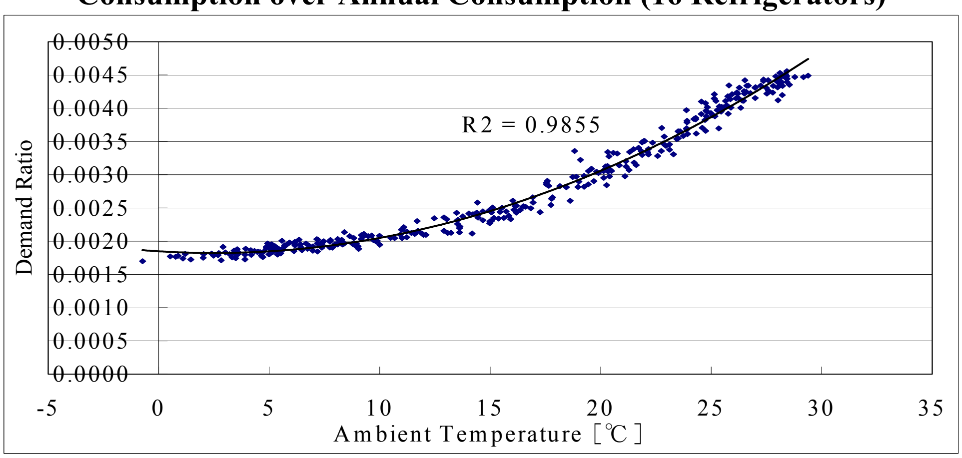


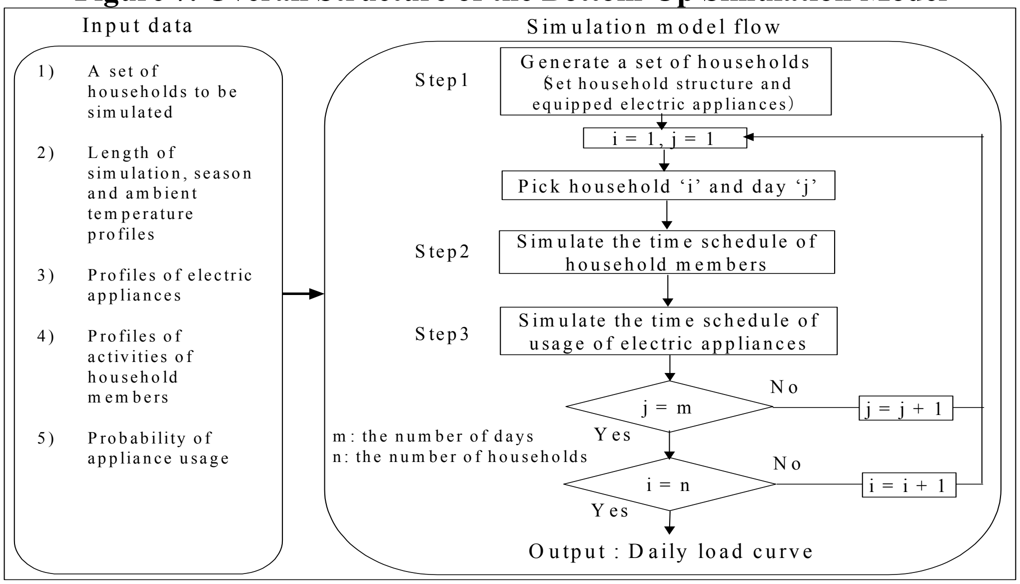
Figure 6. Correlation Between Ambient Temperature and the Ratio of Averaged One Day Consumption over Annual Consumption (16 Refrigerators)



Overall Structure of the Developed Model

Figure 7 describes the overall structure of the developed model in which the list of input required to run the simulation model is clearly shown. A number of households with different structures and a different set of appliances are generated in the computer model and for each household, the electric power consumption is calculated over a number of different representative days. The output of the model will be the power load curves over a set of different representative days, as a result of summing up each of the end-use purposes.

Figure 7. Overall Structure of the Bottom-Up Simulation Model



Simulation Results and Comparison with the Monitored Data

The use of actually measured energy consumption data is most effective for verifying the performance of the developed model. In this section, the daily load curves generated by the developed bottom up simulation model and the results from the monitoring project are compared with each other.

Monitoring Project [Tsuji 2000]

The authors monitored electric power and city gas consumption of residential houses in a small town located near the cities of Kyoto and Nara. The monitoring project started in Oct. 1998 and ended in March 2002. A total of 66 detached houses were monitored. For electric power consumption, most of the domestic appliances in each house were monitored except lighting apparatus. The power consumption over a period of 30 minutes was monitored. From the results of this monitoring project, the daily electric load curves disaggregated by a set of end-use purposes were obtained. The monitored houses are mostly "standard" (2 adults and 2 children), and average size of the houses is around 120m^2. They include a number of typical energy systems in Japanese residential houses. Total energy consumption (electricity, city gas and kerosene) of these houses was distributed over a wide range (30-85GJ/year). These represent a relatively new class (in various aspects such as floor area, number of rooms, many of which pre-fabricated by large manufacturers at a similar price) of houses in Kansai region of Japan.

Preparation of Input Data to the Model and Tuning

The number of houses for which electric power consumption curves were disaggregated into end-use purposes and used for comparison here is 30. Table 1 shows the structure of these households. The structure of family will have much influence on how energy is consumed in a house and therefore Table 1 also represents an essential part of the set of input data for the developed model. Table 2 shows the appliances and their attributes that are also used as one of the required inputs to the model. The minimum and maximum values for unit power consumption of appliances reflect those in the monitored houses. The simulation is also for 30 houses.

In the previous section it was pointed out that the $P_{usage}(j/k)$ can be considered as a set of adjustable parameters. Here, the $P_{usage}(j/k)$ is adjusted by using a set of data from 17 monitored houses (some of them are overlapped with the 30 houses to be simulated) so that the difference between the simulated results and the monitored results becomes small as possible. Note that no mathematical method (such as least square minimization) is introduced here because this $P_{usage}(j/k)$ is a probability that relates an activity k to the use of appliance j which is considered to be insensitive to the individual situation. The values of $P_{usage}(j/k)$ after this fitting are shown in Table 3. Note that the time of the day is divided into four periods and the values are assumed constant for each period in order to avoid many incomprehensible parameters.

Table 1. Structure of Households under Study

House type	Worker	Female at home	Children	College student	Aged person	Component ratio [%]
21	1	1	0	0	0	10
33	1	1	0	1	0	6
34	2	1	0	0	0	3
41	1	1	2	0	0	49
42	1	1	1	1	0	10
44	3	1	0	0	0	3
46	2	0	1	1	0	3
47	2	0	2	0	0	10
51	1	1	3	0	0	6

Results of Comparison

Figures 8 and 9 show the simulated and monitored results for some of the appliances popular in Japanese houses such as TV, rice cooker, air-conditioner for space cooling and appliances for space heating (these contain kotatsu, electric heater and air-conditioner). These curves are obtained by averaging over 30 houses. Figure 10 show the load curves for the whole house from the bottom up simulation model and from the monitored data. It can be observed that the simulated curve for space cooling in Fig. 9(a) is larger than the measured curve in late afternoon to evening in July and September. In Fig. 9(b), power consumption of space heating appliances during the daytime in the simulation model is about half of the monitored results. The reasons for these differences have yet to be analyzed. However, it can be stated from Fig.10 that the seasonal differences of load curves for each end-use purpose are well reproduced by the developed model, although there is some discrepancy between the model output and the actual curves.

In order to see if the developed model can express structural differences (i.e., composition of end-use energy requirement), the monitored houses were separated into two groups where those houses in one group consumes more energy than any houses in another group. Figure 11 show the simulated and monitored results for these two groups. From these

Table 2. Profiles of Appliances for Households under Study

Appliance	Activity category	Operational mode	Duration of operation [min]		Unit power [W]		Standby power [W]		Limited on repeated usage [times]	Saturation rate [%]
			Min	Max	Min	Max	Min	Max		
Lighting (common)	At home	Semi auto	15	15	125	250	0	0	999	100
Lighting (individual)	At home	Semi auto	15	15	100	150	0	0	999	100
Refrigerator	---	Auto	---	---	400	1100	0	0	999	110
Air conditioner/ Heat Pump (cooling)	At home	Semi auto	---	---	200	1000	0	10	999	87
Heat Pump (heating)	At home	Semi auto	15	15	200	1200	0	10	999	57
Gas air conditioner	At home	Semi auto	15	15	20	60	0	8	999	19
Electric fan heater	At home	Semi auto	15	15	300	900	0	0	999	19
Gas fan heater	At home	Semi auto	15	15	14	32	0	8	999	38
Electric carpet	At home	Semi auto	15	15	100	450	0	0	999	48
Kotatsu	At home	Semi auto	15	15	80	250	0	0	999	19
Electric rice cooker	Cooking	Semi auto	30	60	200	500	0	10	3	70
Microwave oven	Cooking	Semi auto	15	15	100	800	0	10	2	100
Vacuum cleaner	Cleaning	Manual	15	75	300	900	0	0	2	98
Hair dryer	Personal matter	Manual	15	15	900	1500	0	0	1	85
Clothes washer	Washing	Semi auto	15	60	100	200	0	0	2	100
Clothes dryer	Washing	Semi auto	15	60	700	900	0	0	4	25
TV (first)	TV watching	Manual	15	15	70	210	0	10	999	100
TV (second)	TV watching	Manual	15	15	70	210	0	10	999	74
CD player	Record & CD	Manual	15	120	10	80	0	10	999	58
VCR	Video	Manual	30	120	100	250	0	10	999	72
Personal computer	Contact mass media	Manual	15	120	100	250	5	10	999	50
Word processor	Contact mass media	Manual	15	120	50	100	5	10	999	50

Table 3. Probability of Appliance Usage

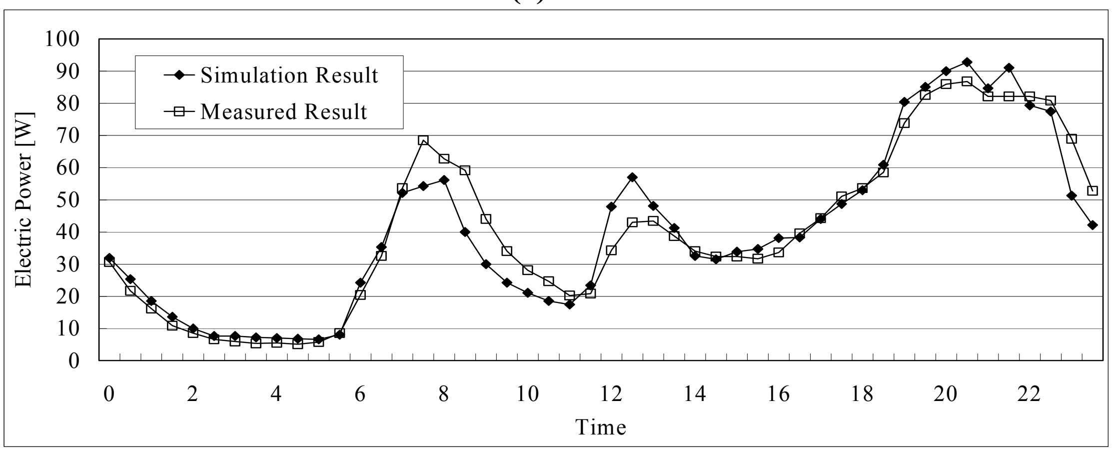
Appliance	Hours 0 – 4 after bedtime	Hours 4 – 10 after getting up	Hours 10 – 17 after going out	Hours 17 – 24 after coming home
Lighting (common)	70	100	70	100
Lighting (individual)	80	70	70	80
Refrigerator	100	100	100	100
Air conditioner/ Heat Pump (cooling)	---	10	30	90
Heat Pump (heating)	50	50	30	50
Gas air conditioner	30	70	40	80
Electric fan heater	40	80	40	70
Gas fan heater	40	80	40	70
Electric carpet	40	30	40	60
Kotatsu	40	50	40	70
Electric rice cooker	50	85	50	85
Microwave oven	25	40	25	40
Vacuum cleaner	90	90	90	90
Hair dryer	30	30	30	30
Clothes washer	100	100	100	100
Clothes dryer	80	80	80	80
TV (first)	90	100	90	100
TV (second)	70	70	30	70
CD player	100	100	100	100
VCR	100	100	100	100
Personal computer	10	10	40	40
Word processor	5	5	20	20

figures one can see that the developed model can reproduce the difference between these two groups reasonably well.

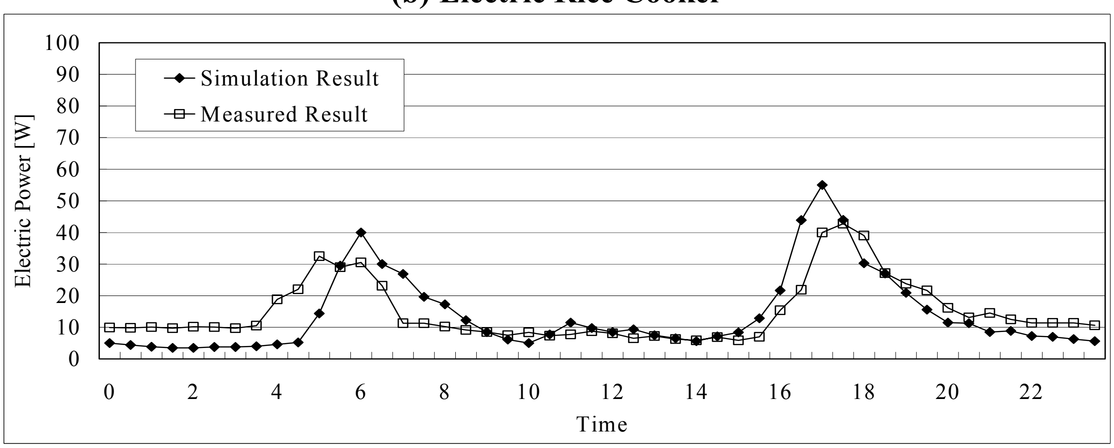
As a whole, it can be concluded that the bottom up simulation model can reproduce major characteristics of the daily load curves quite well even if though the structure of the model is rather simple.

Figure 8. Load Curve of Typical Appliance (Averaged Over 30 Houses, Weekdays, Annual Average)

(a) TV



(b) Electric Rice Cooker

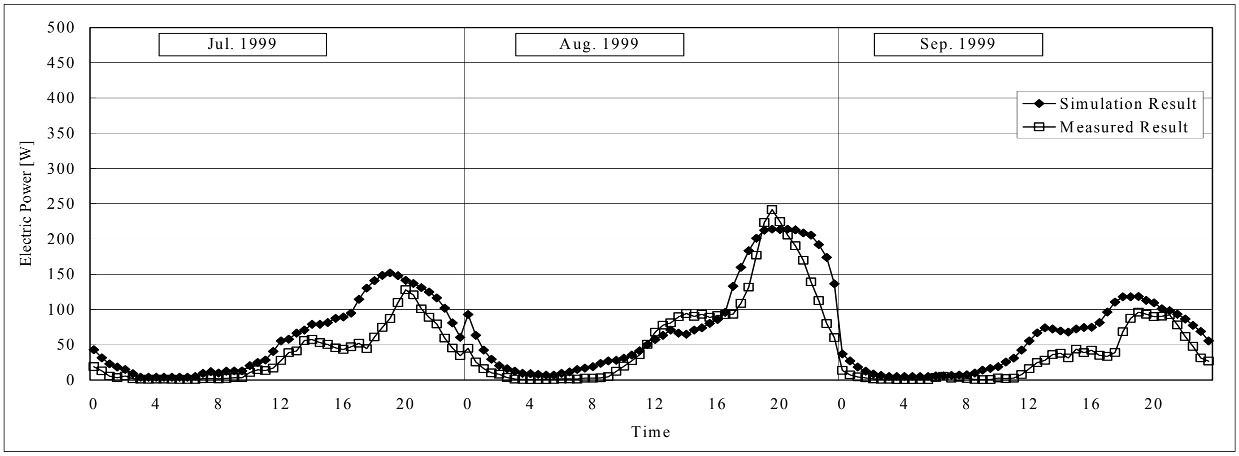


Conclusion

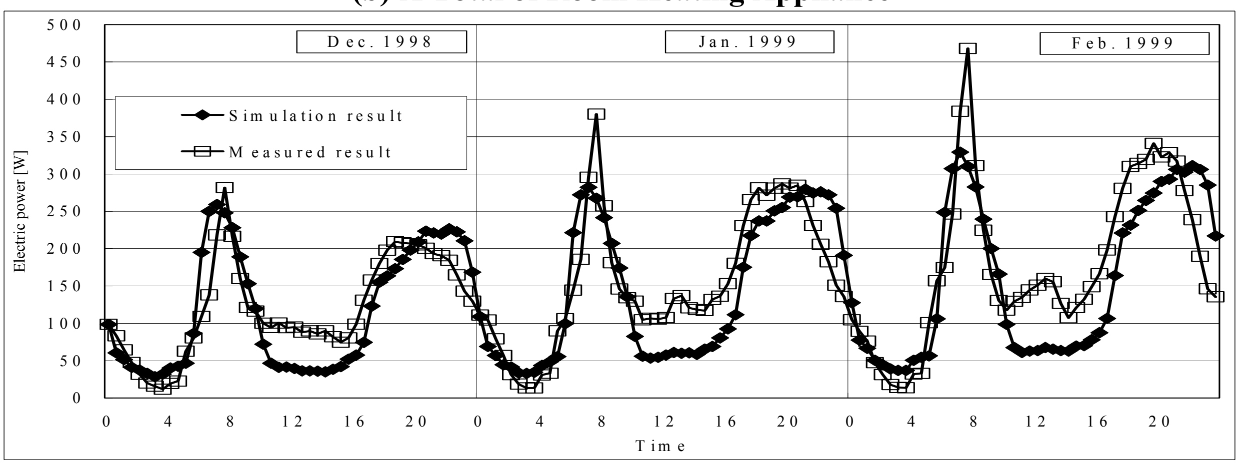
A bottom up simulation model for estimation of load curves was described and some simulation results are shown in comparison with monitored results. The developed model was shown to be able to reproduce daily electric power load curves for different seasons of the year, and for different classes of energy consumption reasonably well, despite the fact that the structure of the model is simple.

Figure 9. Load Curves of Temperature Dependent Appliances (Averaged over 30 Houses, by Month)

(a) Air Conditioner (Cooling)



(b) A Total of Room Heating Appliance



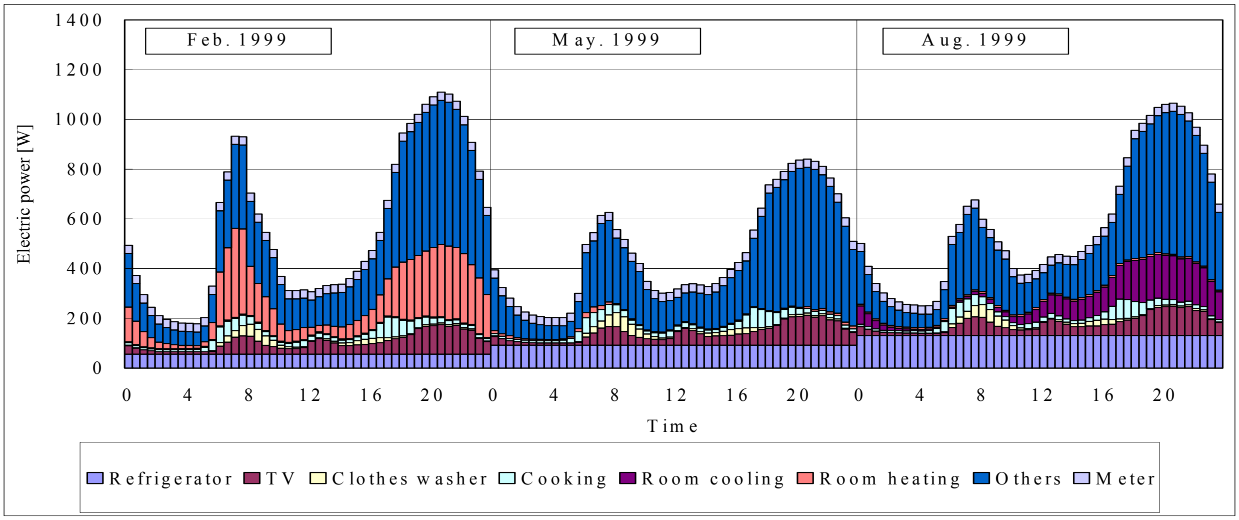
The probability of appliance usage illustrated in Table 3, is identified by utilizing the monitored data and it may well be specific to the monitored houses. However, at the same time, it may sufficiently be stable so that the identified probability could be applicable to a wide range of households. Whether or not the developed model can be applied to other set of houses and in different region still remains as a question to be answered in the future study. More monitored data is necessary in order to further check the range of validity of the model.

Acknowledgments

This work is supported by JSPS (Japan Society for Promotion of Science) Research for the Future program (JSPS-RFTF97P01002). The authors are grateful to those people who contributed to the completion of the research project. The authors extend their sincere appreciation to Mr. Daisuke Shimazaki who did most of the calculation in this paper as a part of his work for Master's thesis. Appreciation is also extended to the reviewers for their valuable and constructive comments and advice.

Figure 10. Comparison of Load Curves of the Whole House (Averaged over 30 Houses, by Season)

(a) Output of Bottom-Up Simulation Model



(b) Monitored Data

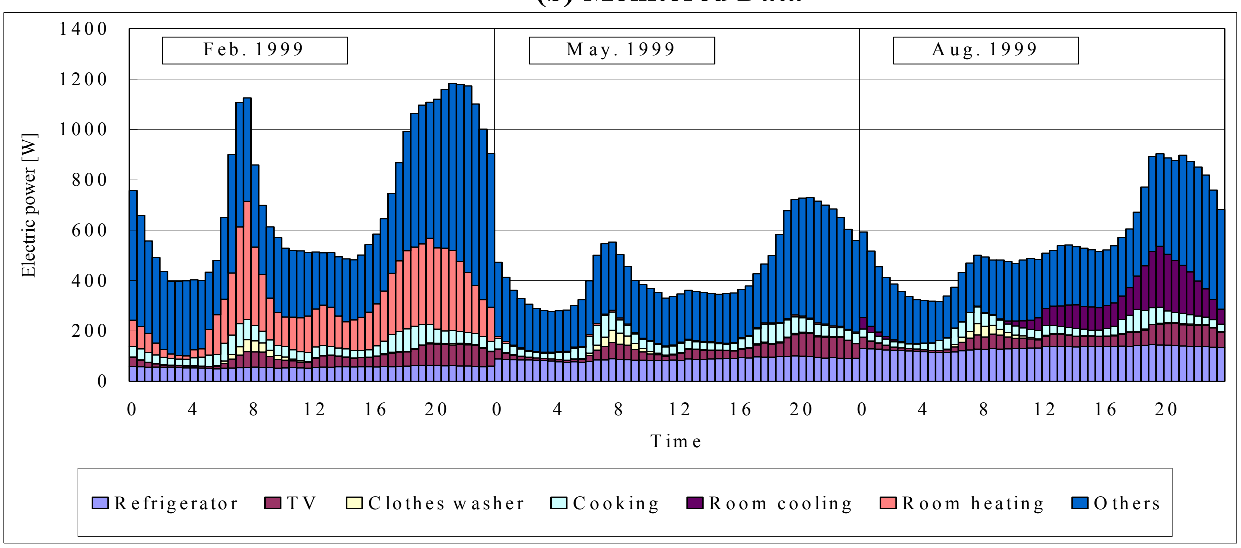


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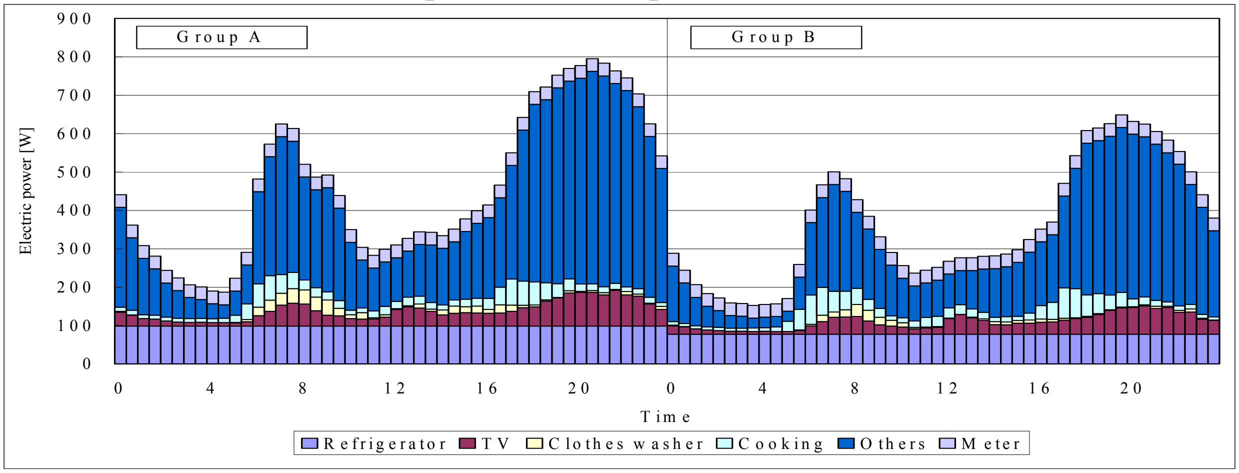
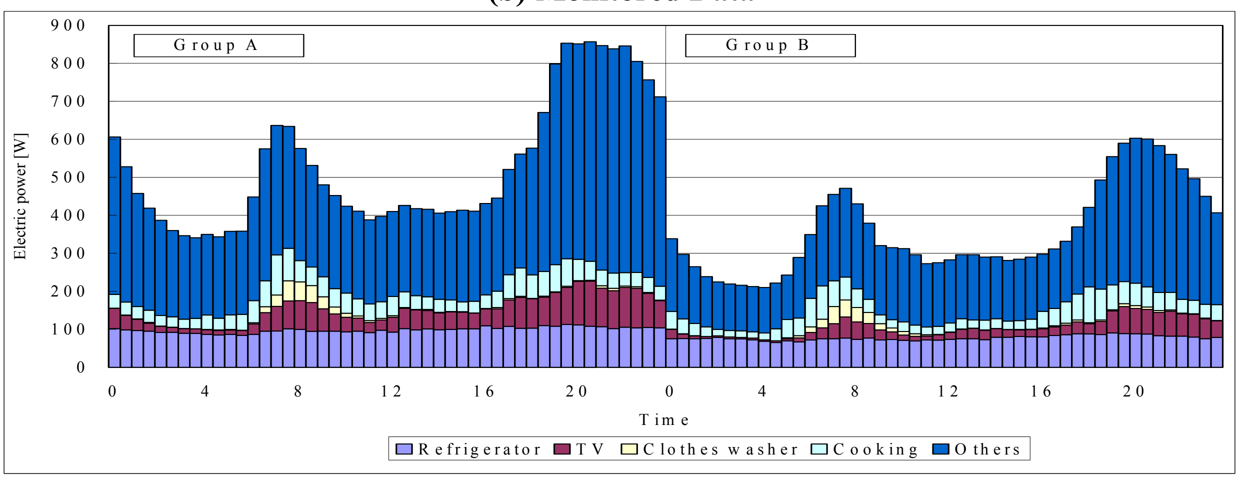
Figure 11. Comparison of Load Curves of the Whole House (Spring and Autumn, by Different Groups)

(a) Output of Bottom-Up Simulation Model



(b) Monitored Data



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