Validation of the Probabilistic Methodology to Generate Actual Inhabitants' Behavior Schedules for Accurate Prediction of Maximum Energy Requirement

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ABSTRACT

A data set of myriad and time-varying inhabitant-behavior schedules with a 15-minute time resolution, generated by the authors in a previous study, is validated through a comparison analysis. We show three comparisons. The first and second compare the estimated demand with a time series of actual utility demand. The comparisons indicate that the generated data and its algorithm, described by the authors, have an appropriate robustness. Another comparison between the estimate and the annual averaged daily water demand of a residential area, consisting of 9,327 residences, also shows an acceptable consistency.

KEYWORDS

inhabitant's behavior schedule, residential building, time series of energy demand

INTRODUCTION

To accurately estimate a space-integrated maximum requirement such as a building total or an urban area total load, we have presented time-varying raw inhabitants' schedule data and a generating algorithm that uses only a statistical database available to the public (Tanimoto et al., 2005, 2007). The algorithm is based on the "generate & kill" process. The data format of the inhabitant-behavior schedule (generated by the authors) is schematically shown in Fig. 1, where uniquely defined terms "Head" and "Tail," shown in Table 5, are also explained. This method of generating each individual's behavior schedule does not produce a utility-demand time-series directly; however, by defining the links between each behavior and an energy-consuming event (plus its demand unit), we can convert that into a respective time series of electricity, gas, water, heat, etc. This provides a plausible estimation of the maximum requirements through a space-averaging operation.

The present study uses three different comparisons to validate these estimated energy and water supply demands.

The first trial compares the estimated demand with a time series of actual utility demand for two residential apartment buildings. This will reinforce the plausibility of our approach. The data compared with the estimated time series is for a family-type residential building of the Ojima Lab's Demand Unit Data (OL-DUD), which is the best known, most widely applied, and highly reliable demand unit data in Japan (Ojima Laboratory, 1995). This kind of demand unit data, especially in the form of day-long time-series, is useful in various situations such as when designing urban energy plants.

The second validation compares the estimated demand with a time series of actual utility demand, based on a long-term, span-field measurement campaign by Maeda et al (2004).

For the third validation, we compare the estimate with the actual average annual daily water demand for 9,327 residences in Kugahara, Tokyo.

ASSUMED SETTING FOR ESTIMATION TO EMULATE OL-DUD TIME SERIES

Table 1 presents a summary of related literature (Hong, 1993 & Akimoto et al., 1992) in the form of fundamental information about two field-measured buildings that provided the family-type residential building's OL-DUD.

Although there was no floor plan information in the previous studies, we assume that condo A is 3 rooms plus a multiple space of living, dining, and kitchen (3LDK) and condo B is 4LDK. Family distributions amid the measured sample dwellings with a definition of respective family types are also assumed. These assumptions (required for the schedule-generating process) are summarized in the lower panel of Table 1.

Field measurement was carried out during August 6th to 7th, 1991, and an averaged time series of power consumption for the electric household appliances (including lighting), cooling power consumption (indicating cooling load), and hot-water energy consumption for the two buildings were obtained with one-hour resolution. The two measurement days were rainy, so the cooling requirement shown as the demand unit data does not seem appropriate for typical summer demand. Therefore, in this study, we used only the power consumption for electric household appliances and hot-water energy. If we do not include the air-conditioning load, we can compare the data of other seasons, since OL-DUD also contains winter, spring, and fall data. In fact, they performed two other field measurement campaigns at the same dwellings during two days of fall and winter, 1991.

A measurement spanning only two days might seem to provide insufficient samples; however, as shown in Table 1, 58 dwellings were simultaneously measured during those periods. The respective measured-demand variations are not significant, but the ensemble-averaged variation is of concern to us. In that sense, although the measured data set provided by OL-DUD is for only two days, because it contains data from 58 dwellings, it has a relatively high robustness. The ensemble-averaged variations of respective seasons can represent 116 (=2 × 58) daily variations. From a statistical point of view, sets of 116 samples is not perfect for calculating an average, but it is substantially acceptable for validating our method.

DEFINITIVE LINKS BETWEEN BEHAVIOR AND ENERGY-CONSUMING EVENTS

Since we have the time series for dynamic inhabitants, producing an energy-consumption time series requires defining an explicit relationship between each behavior, an energy-consuming event, and its demand unit. In practice, one must define both the hot-water demand specification, as well as which electric household appliance is used and how it is used. The electric appliances are divided into two classes: part of the lighting-power load and general household appliances.

Hot water demand

Referring to the previous study (SHASE, 2000), we assume that there are three separate hot water demands on a daily basis: individual morning events including face washing, bath-related events, and dining events including washing dishes. Following Japanese custom, bathing should further be considered as two different events—showering and filling the bathtub. The relationships between these events and the assumed generating behaviors are shown in Table 2. To transform this information into an energy demand time series, we must follow the general formula:

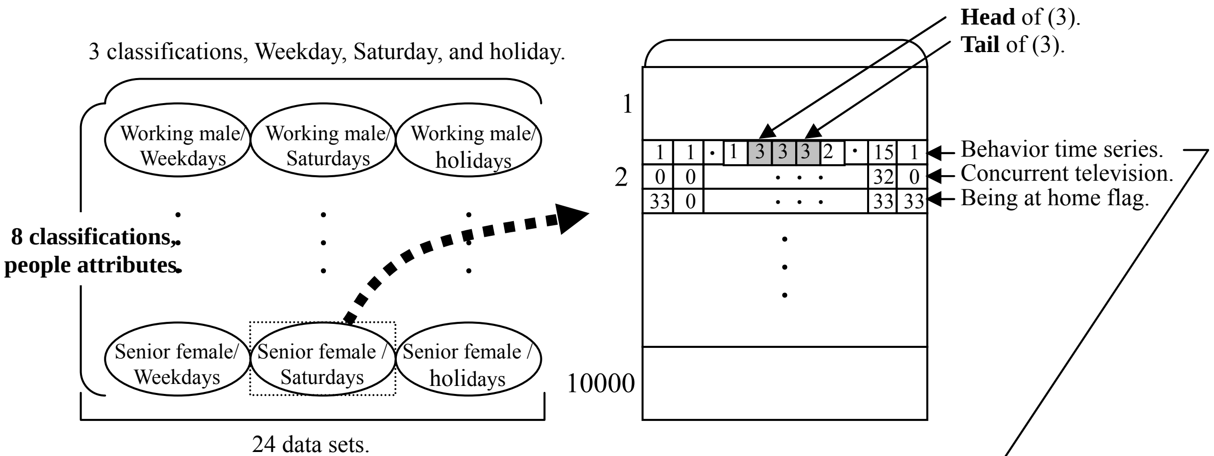
(Energy requirement [J/event]) =
(Specific heat of water [J/m^3]) ×
(Required volume, V_{hw} [m^3/event]) ×
{(Hot water temperature, T_{hw} [℃]) − (Supplied water temperature, T_w [℃])}.

Table 3 shows our assumptions. Both assumptions, V_{hw} and T_{hw}, are from the previous study (SHASE, 2000). T_w is assumed according to public data issued by the City-Water Bureau of the Tokyo Metropolitan Government.

Lighting power demand

We assume 5 W/m^2 as the lighting power demand unit (SHASE, 2000). Lighting is assumed to be on when a family member is present in the room during lighting-possible hours. The relationships between respective rooms and the generated behaviors are shown in Table 4. The lighting-possible hours are defined based on seasonal daylight hours as

Summer: 1–6 am & 6–12 pm,
Winter: 1–7 am & 5–12 pm,
Spring &fall: 1–5 am & 6–12 pm.



- A user randomly selects one of the 10,000 samples of each data set, when he/she requires an individual inhabitant's schedule.
- A user randomly selects each one of the 10,000 samples and combines them, when he/she requires a family schedule.

Classification of behaviors

(1) Sleeping (2) Dining (3) Fundamental acts to fulfill daily needs (4) Resting and hospitalizing (5) Working (6) Social relationships from working affairs (7) Class and lecture (8) Extracurricular activities (9) Cooking, cleaning, and laundering (10) Cooking (11) Cleaning (12) Laundering (13) Shopping (14) Childcare (15) Household chores (16) Commuting (17) Schooling (18) Social activities (19) Conversation and personal relationships (20) Sports (21) Leisure and exercise (22) Hobby and cultural activities (23) Television (24) Radio (25) Reading newspaper (26) Reading magazines and comics (27) Reading books (28) Listening to music (29) Watching videos (30) Resting (31) Other activities

Fig.1. Data format of the inhabitant behavior schedule generated by the authors.

Table 1 Reported information on two residential buildings for the field measurement that provided Ojima Lab's Demand Unit Data of familial type residential building and assumptions to generate behavior schedule.

Building and its location			Condo A. Niiza City, Saitama Prefecture.	Condo B Kawasaki City, Kanagawa Prefecture.
Reported information	Area [m^2]	[ave. ± s.d.]	77.9 ± 6.9	101.4 ± 8.6
	Head count per family	[ave. ± s.d.]	3.3 ± 1.0	3.8 ± 0.6
	Measured samples (Entire number of dwellings)		32（134）	26（125）
Assumption	Floor plan		3LDK (77.9 m^2)	4LDK (101.4 m^2)
	Family distribution		Couple-family: 8 Trio-family: 11 Quartet-family: 7 Quintet-family: 6 Total 32 families	Couple-family: 2 Trio-family: 6 Quartet-family: 12 Quintet-family: 6 Total 26 families
	Head count per family	[ave. ± s.d.]	3.34 ± 1.01	3.85 ± 0.64

Several important definitions

- 3LDK; 1) living & dining room with kitchen (LDK) [26.4 m^2], 2) Japanese style Tatami room [10.7 m^2], 3) main bed room [13.2 m^2], 4) child room [10.2 m^2], 5) bathroom [8.2 m^2], 6) lavatory [1.32 m^2], and 7) vestibule hall [9.9 m^2].
- 4LDK; 1) living & dining room with kitchen (LDK) [29.9 m^2], 2) Japanese style Tatami room [12.1 m^2], 3) main bed room [14.9 m^2], 4-1) child room #1 [11.6 m^2], 4-2) child room #2 [10.9 m^2], 5) bathroom [9.3 m^2], 6) lavatory [1.54 m^2], and 7) vestibule hall [11.2 m^2].
- Couple-family consists of working male (father) and housewife (mother). Trio-family consists of working male, housewife, and elementary school child (Child#1). Quartet-family consists of working male, housewife, high

Power demand for other electric household appliances

Hong (1993) reported on the electric household appliances owned by residents, by listing their probabilities for condo A and B. We assume the relationship between these appliances and the behavior as shown in Table 5. In the calculations, electric power consumption is calculated by dividing the power into active and standby power. Rated power loads for respective appliances are assumed as general and averaged values under dissemination.

RESULTS AND DISCUSSION

Fig. 2 shows a comparison of the time series for hot water energy and electricity demand between estimated and OL-DUD values. The estimated time series are accurate, although there are peak discrepancies of hot water demand in every season. The hot water peaks during evening hours can be attributed to bath-related events, where the estimated time series are heading 1-2 hours to OL-DUD, real demand time series.

These discrepancies can be explained in several possible ways.

One is the possibility that the inhabitant's behavior schedule is inaccurate for several hours before the sleeping event. "(1) Sleeping" is relatively long vis-à-vis other behaviors, which can be likened to a large puzzle piece in the process of "generate & kill"—just like hole-filling by a set of puzzle pieces. This fact inevitably implies a lack of freedom around the event of sleeping.

The original statistical data used to generate a schedule was derived from the NHK's (Nippon Hoso Kyokai (Japan Broadcast Institution)) investigation (NHK, 2000), covering all of Japan. Thus, the generated behavior schedule simulates an averaged time series for the whole country. However, as mentioned above, OL-DUD pertains to two actual buildings in Tokyo. Generally, people living in Tokyo stay up rather late at night compared with people living in other local areas. This may be one of the causes of the peak discrepancies.

LONG PERIOD COMPARISON

As previously mentioned, OL-DUD pertains to a two-day measurement period. In the second comparison, we refer to another time series of actual utility demand, collected by Maeda et al (2004) at 18 dwellings in a residential building in Fukuoka. Each dwelling is 3LDK, having the same floor area of 68 m^2, of which head count per dwelling (family size) was reported as 3.78 ± 0.87 (accurate family size information of the respective 18 dwellings was investigated and is reported.). Electric power consumption, hot water energy, and gas consumption were precisely measured over a period of 15 months (from Mar. 2003 to Jun. 2004). We assume the same

Table 2 Hot water supply events and the definition of what "behavior" accompanies the event.

Hot water supply events.	Assumption regarding what "behavior" accompanies the hot water supply event.
Washing face, shaving, combing hair in the morning	At the head of (3) Fundamental acts to fulfill daily needs at the beginning of the day when the inhabitant is at home.
Bath/showering with bathtub serving	At the head of (3) Fundamental acts to fulfill daily needs after 6 pm when the inhabitant is at home.
Bath/filling bathtub	Immediately before the head of (3) Fundamental acts to fulfill daily needs of one of the family members who makes it earliest after 6 pm.
Dishwashing after dining	Immediately after the tail of (2) Dining when the inhabitant is at home.

Table 3 Assumptions for calculating the hot water supply

		Summer		Winter		Spring & Fall	
T_w [℃]		23.6		8.5		18.5	
		V_{hw}	T_{hw} [°C]	V_{hw}	T_{hw} [°C]	V_{hw}	T_{hw} [°C]
Washing face, shaving, combing [hair]in the morning		0.0105	39.0	0.0105	38.0	0.0105	38.3
Bath	Showering with bathtub serving	0.0186	37.7	0.0152	39.0	0.0165	38.3
	Filling bathtub	0.2	41.5	0.2	44.0	0.2	42.5
Dishwashing after dining		0.0120	39.7	0.0120	39.0	0.0120	39.7

- The unit of V_{hw} is m^3/(event*person) except for Bath/filling bathtub, which is defined as m^3/(event).
- Filling bathtub is assumed to take place 0.4 event/day for winter and 0.7 event/day for other seasons.

Table 4 Definitions regarding which room the behavior takes place.

Behaviors occurring when the inhabitant is at home.	Room the behavior takes place.
(1) Sleeping, (30) Resting.	Each inhabitant's sleeping room.
(3) Fundamental acts to fulfill daily needs, (12) Laundering.	5) Bathroom.
Children's (8) Extracurricular activities, (23) Television, (26) Reading magazines and comics, (27) Reading books.	4-1) Child room #1 or 4-2) child room #2.
Other behaviors	1) LDK.

The definition of each inhabitant's sleeping room[:] 2) Japanese style Tatami room is for grandmother, 3) main bedroom is for father and mother, and 4-1) child room #1 and 4-2) #2 are for child #1 and child #2, respectively.

list and probability of ownership of electric household appliances as for condo A of OL-DUD (Table 5). Unfortunately, none of this information was reported by Maeda et al (2004); however, the dwelling floor area is close to that of condo A in Table 1. In this comparison, we only focus on the spring & fall measured data, since the electric power consumption for both summer and winter contain cooling and heating energy.

The assumptions of links between each behavior and energy-consuming events are same as previously mentioned. Concerning hot water energy, however, we used a more detailed procedure. In the first comparison, we assumed that the unit V_{hw} is a deterministic variable for respective events, as shown in Table 3. The reality, however, is different. Actual water and hot-water consumption rates, for a single event, differ from person to person. By freely controlling the opening of a faucet, he/she controls how long a faucet is open, except for filling bathtub and toilet flush (these are determined by bathtub or tank capacity). From this viewpoint, Murakawa (1976) reported a probabilistic model to reproduce several water supply demands, based on field-measurement data for residential buildings. He approximated the unit V_{hw} by a series of random numbers obeying Exponential, Erlang, or Hyper-exponential distribution. In his model, most of the unit rates are expressed by Exponential distribution, but a Hyper-exponential distribution is applied to the unit V_{hw} of dining events (including washing dishes). This seems plausible because a water consumption rate for washing dishes is so individual that the probabilistic deviation must be larger than that for other typical events such as filling bathtub and flushing the toilet. Therefore, in our second comparison, we applied the probabilistic model for V_{hw} proposed by Murakawa (1976).

Fig. 3 shows a comparison between estimated and measured values of time series for hot water energy and electricity demand. Respective measured time series are ensemble averages of weekdays, Saturdays, and holidays from both April to May and October to November of the measurement period. In short, respective ensemble averages can represent daily variations of 18 [residents] × (measured sample days).

The estimated time series show acceptable agreement with that of the measured data, although some overestimation of hot water demand is observed in the morning hours. The overestimation may be due to the smaller number of sample dwellings,18, as compared with 58 in OL-DUD. With a small number of sample families, if a few families deviate from the

Table 5 Relationship between assumed functional electric household appliances and user behavior

Electric household appliances	Power use [W] (Standby power use [W])	Holding probability Condo A	Holding probability Condo B	Assumptions regarding the "behavior" of the person when using the appliance, in what room, at what time, and how many minutes it is used.
Rice steam machine	225 (31.0)	0.9	0.9	At the head of (10) Cooking by mother or grandmother after 3 pm when they are at home. Never simultaneously used. Used in LDK and for 30 minutes.
Toaster oven	750 (2.8)	0.9	0.6	At the head of (10) Cooking by mother or grandmother at the beginning of the day when they are at home. Never simultaneously used. Used in LDK and for 5 minutes.
Microwave	200 (2.8)	0.9	0.5	At the head of (10) Cooking by mother or grandmother when they are at home. Never simultaneously used. Used in LDK and for 5 minutes.
Hot water pot	— (66.0)	0.6	0.6	Only standby but used for 24 hours. In LDK.
Video	120 (6.2)	1	1	For the entire period of (29) Respective inhabitants watching videos when they are at home. Never simultaneously used. In LDK.
Radio, CD player	100 (14.0)	0.5	0.5	For the entire period of (24) Respective inhabitants (28) Listening to music and radio when they are at home. Never simultaneously used. In LDK.
PC	300 (1.5)	0.3	0.3	For the entire period of (22) Hobby and cultural activities of respective inhabitants when they are at home. Never simultaneously used. In LDK.
BS tuner	— (12.3)	0.2	0.2	Only standby but used for 24 hours. In LDK.
FAX	— (20.0)	0.4	0.4	Only standby but used for 24 hours. In LDK.
Phone	— (5.0)	1	1	Only standby but used for 24 hours. In LDK.
Toilet seat warmer, toilet hot water supplier	Summer:- (23.0) Winter:- (35.0) Spring & fall: - (27.0)	0.5	0.5	Only standby but used for 24 hours. In lavatory.
Air conditioner	— (2.6)	1	1	Only standby but used for 24 hours (because cooling load is another problem). There is an air-conditioner in each LDK, main bed room, child room #1, and child room #2.
TV	120 (2.0)	1	1	For the entire period of (23) watching TV and (32) Concurrent TV by respective inhabitants when they are at home. If the inhabitant is father, mother, or grandmother, this happens in LDK; never simultaneously used. If the inhabitants are Child #1 and/or #2, this happens in child room #1 and/or child room #2.
Refrigerator	— (66.0)	1	1	Only standby but used for 24 hours. In LDK.
Fan	20 (—)	1	1	1) At the head of (10) Cooking by mother or grandmother when they are at home. Never simultaneously used. Used in LDK and for 15 minutes. 2) At the head of (3) Fundamental acts to fulfill daily needs of respective inhabitants after 6 pm when they are at home. Never simultaneously used. Used in bath room and for 15 minutes.
Laundry machine	126 (—)	1	0	For the entire period of (12) Laundering by mother or grandmother when they are at home. Never simultaneously used. In bath room.
Laundry dryer	1300 (—)	0.7	0	For the entire period of (12) Laundering by mother or grandmother when they are at home. Never simultaneously used. In bath room. Since it was confirmed to be rainy on Aug. 6–7, 1991, we assume the probability of use in summer is 0.5, but during other seasons it is 0.
Hair dryer	450 (—)	1	1	For 3 minutes during the period of (3) Fundamental acts to fulfill daily needs of respective inhabitants before 9 am and after 6 pm whe they are at home. In bath room.
Personal lighting	30 (—)	1	1	1) For the entire period of (8) Extracurricular activities, (26) Reading magazines and comics, and (27) Reading books by Child #1 and/or Chile #2 when they are at home and during lighting-possible hours. In child room #1 and/or child room #2. 2) For the entire period of (25) Reading newspaper, (26) Reading magazines and comics, and (27) Reading books by father, mother, or grandmother when they are at home and during lighting-possible hours. Never simultaneously used. In LDK.
Cleaner	200 (—)	1	1	For the entire period of (11) Cleaning by mother or grandmother when they are at home. It is used in every room, and so the power consumption is fairly divided based on the weight of the respective room areas. Never simultaneously used.
Cloth presser (Iron)	500 (—)	1	1	At the head of (12) Laundering by mother or grandmother once a day for 10 minutes in Japanese style Tatami room. Never simultaneously used.
Fanner	Summer: 40 (–)	0.7	0.2	It is always turned on if someone is in LDK.
Kotatsu*1	Winter: 800 (–)	0.7	0.2	It is always turned on if someone is in LDK.
Electric range	2600 (—)	0.1	1	At the head of (10) Cooking by mother or grandmother when they are at home. Never simultaneously used. Used in LDK and for 15 minutes. Never simultaneously used.
Futon*2 dryer	500 (—)	0.2	0.2	At the head of (12) Laundering by mother or grandmother once a day for 15 minutes in Japanese style Tatami room. Never simultaneously used.

*1 Kotatsu is a Japanese traditional foot warmer that is used as a heating apparatus. *2 Futon is Japanese traditional bedclothes.

typical time series, the entire ensemble average is inevitably affected.

WATER SUPPLY COMPARISON

For further validation of the inhabitants' behavior

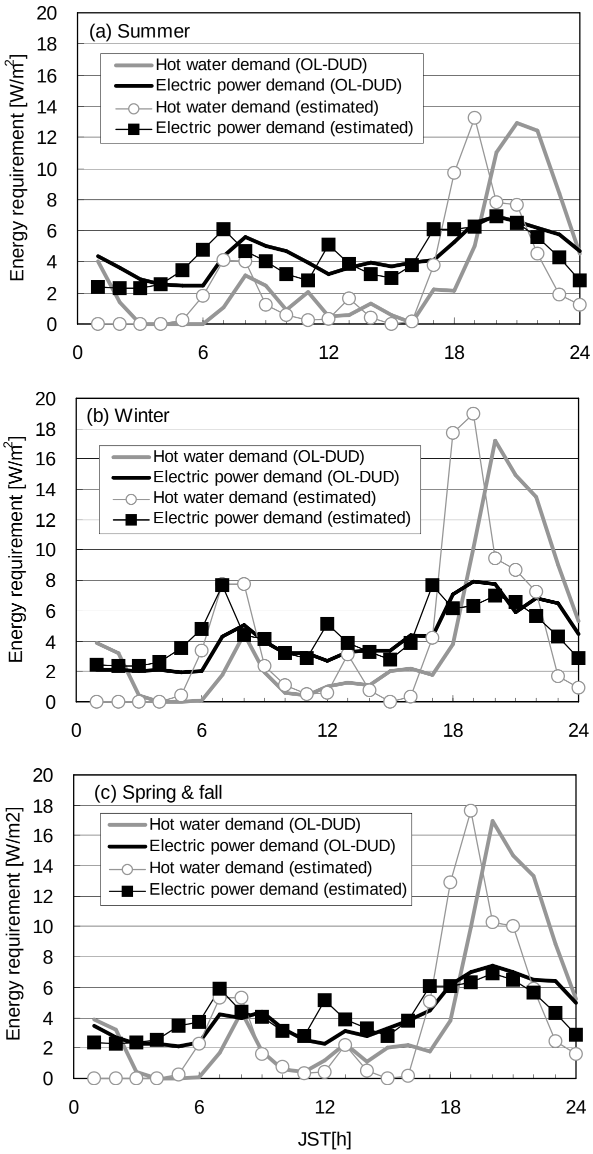


Fig.2. Comparisons of the observed (OL-DUD) and estimated time series of energy

schedules, we compared our estimation with the actual city water consumption for the 9,327 residences in Kugahara, Tokyo (average annual daily consumption). In 2003, the actual amount of city water supplied, as measured by the Bureau of Waterworks, Tokyo Metropolitan Government, was 6,659 m^3/day. Considering the actual familial distribution of these 9,327 residences (population of 21,982, based on the 2000 National Census), the inhabitants' behavior schedules in the respective 9,327 residences are generated according to the above-mentioned procedure. Assuming the hot-water supply events listed in Tables 2 and 3, plus *Cooking* (happening immediately before the head of <u>(2) Dining</u>); V_w = 0.010 m^3/(event*·person), *Toilet* (happening 0.5 event/hour when the inhabitant is at home and not sleeping); V_w = 0.012 m^3/(event*·person), and *Laundry* (happening at the head of <u>(12) Laundering</u>); V_w = 0.140 m^3/(event*family), we summed the daily total

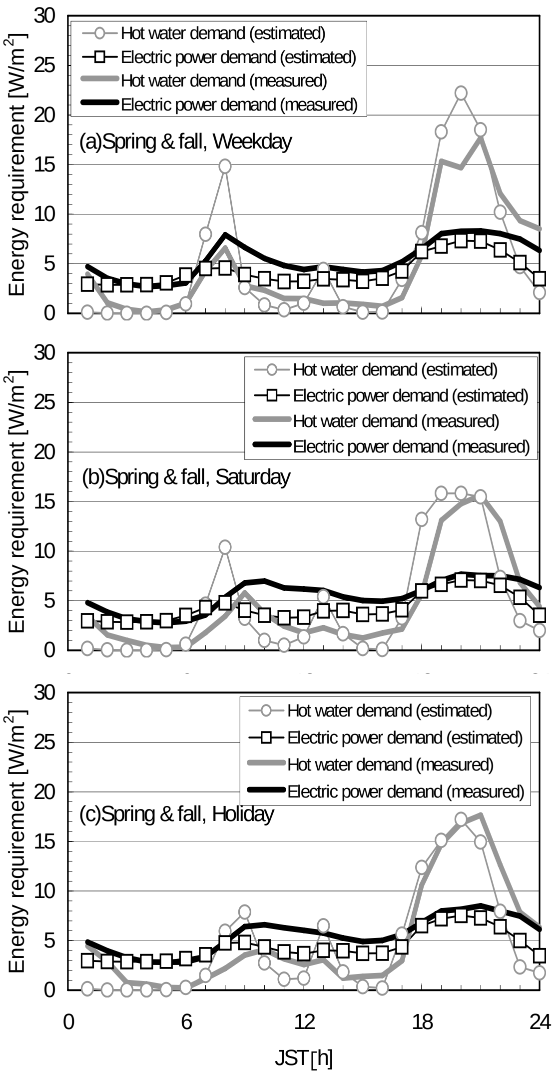


Fig.3. Comparisons of the observed (by Maeda et al. (2004)) and estimated time series of energy requirements.

consumption for all 9,327 residences, which is shown in Fig. 4. The estimated amount is almost consistent with the public data—6,659 m^3/day. The estimated consumption can be divided into daily breakdowns (Fig. 4) and its time series (Fig. 5).

CONCLUSION

To validate the plausibility of generated inhabitants' behavior schedules in a time series form, we performed three different comparisons.

First, we compared our estimated energy requirement time series with actual ones obtained from two residential buildings in Tokyo. The estimated time series were based on the generated inhabitants' behavior schedules and various plausible assumptions of relationships between each behavior and an energy-requirement event. Also, we compared estimates to actual time series for a family-type residential building from the Ojima Lab's Demand Unit Data, which seemed to be reliable from a practical research point of view. A comparison of the two types of time series for electric household-appliance loads and hot water demand implies a modest plausibility.

For our second validation, we compared our estimates with another actual time series, based on a longer measurement period at a residential building

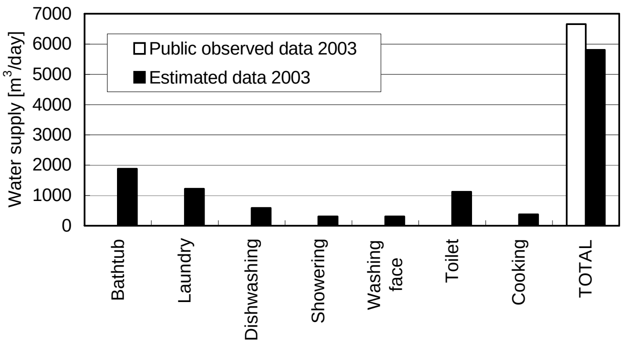


Fig.4. Comparisons of the observed and estimated daily city water demands of 9,327 residences

in Fukuoka, reported by Maeda et al. (2004). We adopted a more detailed probabilistic procedure for hot water supply demands, which was developed by Murakawa (1976). This result also implies the plausibility and applicability of our method.

For the third validation, we compared the estimates with actual annually-averaged daily water demands of some nine thousand residences in Tokyo. This confirmed an acceptable accuracy.

These results show that both the set of generated-schedule data and the generating algorithm proposed by the authors are suitable for various practical applications.

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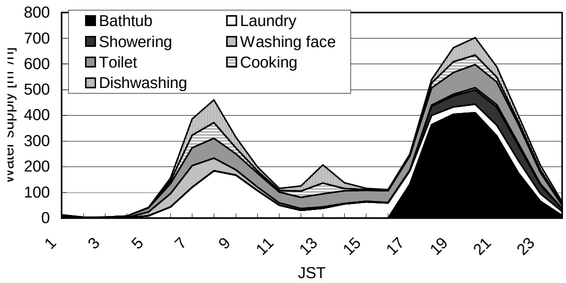

Fig.5. Time series of the estimated city water demand of 9,327 residences.

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