transferred to water to generate an amount of hot water with certain temperature. The heat generated is physically given by the amount of water multiplied by specific heat of water and temperature difference between hot water used and clean water supplied. Thus, the other factors determining energy consumption of water heating are, 2) temperature of clean water, 3) daily hot water use behavior of occupants and 4) quantity of hot water accompanied by each hot water use behavior. Thus, in order to generate realistic hot water demand, the factors 3) and 4) must be realistically modelled.

This paper presents a hot water demand model capable of generating such realistic hot water demand. This paper first explains the procedure of calculating hot water demand. Then, analysis of the measured data conducted to develop a database on hot water quantity accompanied by hot water use behavior is presented. Finally, this paper shows a result of validation of the model using the measured data.

HOT WATER DEMAND MODEL

The hot water demand model was developed as a part of a bottom-up residential energy demand model (Yamaguchi et al. 2014a). In the residential energy demand model, the unit of simulation is a house. The first step of the model is to define a family living in simulated house. Members of family have specific attributes given by age, gender and occupation by which a dataset to generate the daily behavior is given. The dataset is a statistical information of time allocation of people on weekdays and holidays, which is referred to time use data in this paper. This data is used to generate daily behavior of household members stochastically. The model assumes that an amount of hot water is consumed when household members conduct the following behaviors: bathing, showering, bathtub filling, face washing, cooking and dish washing. Then, the daily behavior data is converted to the quantity of hot water given by a database. The quantity of hot water accompanied with each hot water use behavior was mentioned as the fourth factor determining water heating energy consumption. The methodology to quantify the quantity is explained below.

(1) Occupants' behavior model

The time use data contains statistical information on time allocation for 85 kinds of behavior on weekdays and holidays. The data is used to generate behaviors of household members stochastically on simulation days (Yamaguchi et al. 2014b). 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 information on the duration. Then these discrete behaviours are placed on timeline of day by using probability distribution of time allocation. For sleeping, probability distribution is given for ending time, while it is given for beginning time. This is because we observed that standard deviation of awaking time is smaller than sleep beginning time.

After placing all the routine behaviors, the gaps between the routine behaviours are filled by non-routine behaviours. For this 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 data 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, which are mentioned above as time use data. These data are all developed for a variety of occupants attributes' category based on the result of Japanese national time use survey to take into account characteristic in time use of people with different attributes.

(2) Conversion from behavior to hot water use

The daily behaviors that accompanies water use are bathing, showering, bathtub filling, face washing, cooking and dish washing. Hot water demand (Q_{demand} [J]) is defined by Equation (1).

$$Q_{demand} = C_{water} \cdot V \cdot G \cdot \left(T_{demand} - T_{water}\right) \quad (1)$$

where C_{water} [J/kg/ºC] is specific heat of water, V [ℓ] is hot-water quantity, G [kg/ℓ] is specific gravity of water (G = 1.0), T_{demand} [ºC] is hot water supply temperature, and T_{water} [ºC] is clean water supply temperature. The clean water supply temperature (T_{water} [ºC]) is defined by Equation (2) (Nabeshima 1998).

$$T_{water} = a \times t_1 + b \times t_2 + c \times t_3 + d \quad (2)$$

where a, b, c, and d [-] are regression coefficients (a = 0.19, b = 0, c = 0.72, d = 1.28 in Osaka), t_1 [ºC] is average temperature of the day, t_2 [ºC] is average temperature for the past 5 days, and t_3 [ºC] is average temperature for the past 7 days.

DATABASE ON HOT WATER USE

As mentioned above, to determine hot water demand, database on the quantity and supply temperature for each hot water use behavior is used. In order to develop the database on the hot water quantity, we analyzed the data listed in Table 1. This data contains time-series consumption of city gas, water, and electricity collected from 226 households. In these households, city gas is used for cooking and heating besides water heating. By disaggregating city gas and water consumptions into each end use, the quantity of hot water for each behavior were determined for each household. It should be noted that we only quantify the quantity of hot water accompanied by each hot water use behavior. We assumed that the temperature of hot water is assumed to be 40 ºC. As temperature of clean water supply can be given by Equation (2), water quantity accompanied by hot water use behaviors can be quantified by quantifying city gas consumption accompanied by each hot water use behavior. Thus, we disaggregated city gas consumption into the following end uses below: "Bathing and shower", "Bathtub filling", "Face washing", "Cooking and dish washing", "Reheated", "Kitchen", "Space heating".

Table 1. *Outline of measured data*

Area	Osaka
Measurement period	From January, 2012 to December
Number of households	226
Analysis data	City gas, water, electricity consumption
Time resolution of data	1 minute
Kind of water heater	Condensing gas water heater

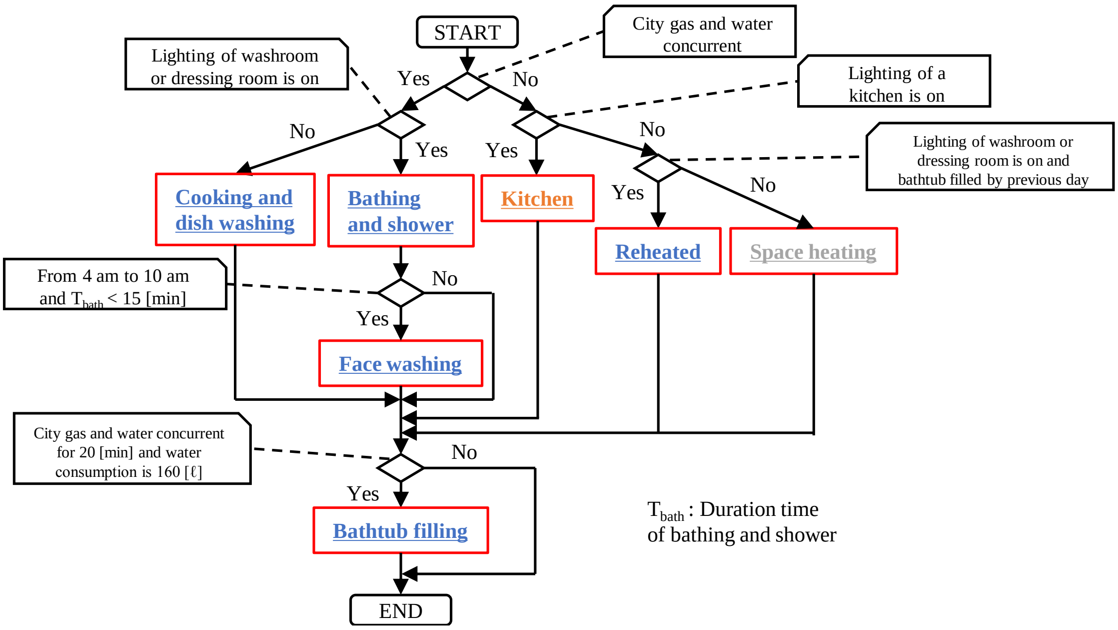

Figure 1. *Procedure to disaggregate city gas consumption*

Procedure to disaggregate city gas consumption

Figure 1 shows the procedure to disaggregate city gas consumption into end-uses. First, we judged if city gas and water are consumed concurrently. If not used concurrently, we further tested if the lighting of a kitchen is on. If yes, the city gas use is labeled as "Kitchen". If the lighting of kitchen is off, the city gas use is labelled as "Space heating". If city gas and water are consumed concurrently, city gas use can be assumed to be for water heating. When the lighting of washroom or dressing room is on, the city gas use is labeled as "Bathing and shower". If the lighting is off, the city gas use is labelled as "Cooking and dish washing". However, this behavior occurred from 4 am to 10 am and the duration of the behavior is less than 15 minutes, the use of city gas is labeled as "Face washing". Additionally, if city gas and water are consumed concurrently for 20 minutes and the total quantity consumed for the 20 minutes is 160 ℓ or larger, the city gas use is labelled as "Bathtub filling".

The quantified city gas quantity is then converted to the equivalent amount of hot water while considering clean water temperature, which was summarized as a cumulative frequency distribution. By using the cumulative frequency distribution, we can randomly generate households with different characteristics in hot water use. This is demonstrated after showing the result for database development.

Result

Figure 2 shows the city gas use disaggregated into the end uses for a representative household on January 7. The figure on the top shows the electricity consumption of lightings in the washroom, dressing room and kitchen. As shown in the figure, we can judge which rooms are used by household members over the day. The figure in the middle shows consumptions of city gas and water. The figure on the bottom shows the result of disaggregation. Table 2 lists the quantity of hot water use for the hot water use behaviors on the day. Figure 3 shows the observed quantities for the representative household summarized in the form of cumulative frequency distribution for seasons. Based on the result, mean quantity for each season was determined. Table 2 also lists the result.

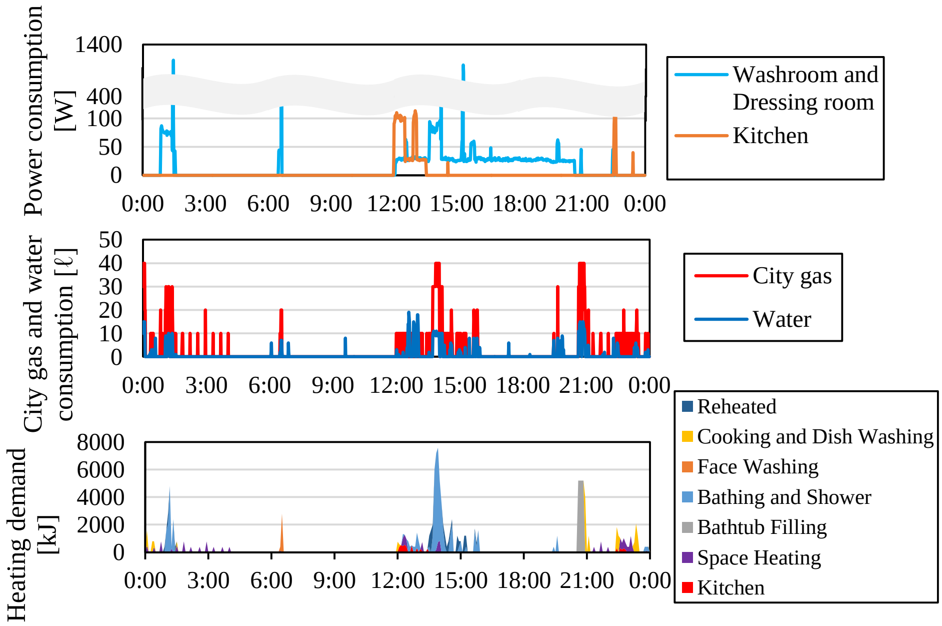

Figure 2. *Disaggregation of city gas use result of a representation household (7-Jan)*

Table 2. *Quantity of hot water use for hot water use behavior*

[ℓ/day]	7-Jan	Winter	Summer	Middle
Bathing and Shower	548	629	492	570
Bathtub Filling	180	187	175	170
Cooking and Dish Washing	121	185	134	191
Face Washing	24	38	55	63

To confirm if the quantities are reliable, we compared them with reference values. Figure 4 shows the mean daily hot water demand quantified by Nakahama et al. (2009) developed based on field measurement from 171 households. As shown in the figure, our result is relatively small than the reference. This might be because Nakahama et al. only targeted households with three to five members, while our result contains couples' ones. Figure 5 compares our result with IBEC's reference (2009).

The error bar shows the range given by standard deviation among households. These figures showed that the developed database is reliable enough to reflect actual hot water demand and its variety among households.

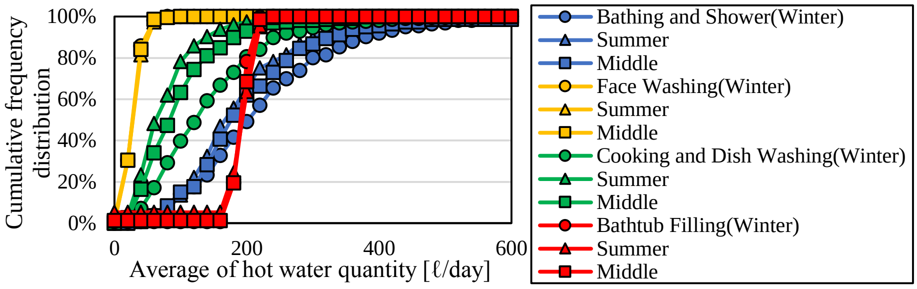

Figure 3. *Cumulative frequency distribution of hot water quantity per day*

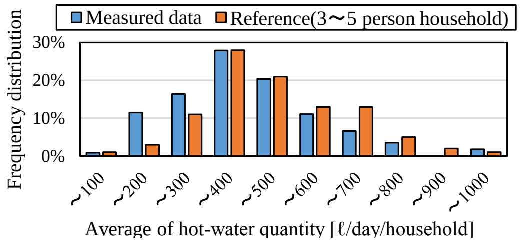

Figure 4. *Comparative result with reference*

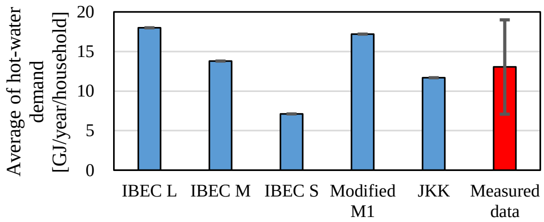

Figure 5. *Comparative result with hot-water test mode*

Development of cumulative frequency distribution

We finally developed a cumulative frequency distribution on the quantity of hot water accompanied with each hot water use behavior. As listed in Table 2, the quantity of accompanied with the hot water use behaviors was quantified for each households. This result was summarized in the form of cumulative frequency distribution. Figure 6 shows the result. By using these distributions, the quantity accompanied with the hot water use behaviors is randomly given to households in the simulation model.

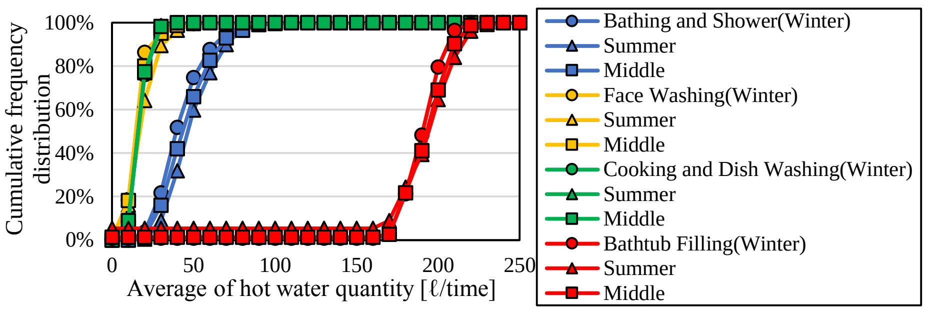

Figure 6. *Cumulative frequency distribution of hot water quantity*

VALIDATION OF SIMULATION MODEL

To validate the hot water demand model, we compared simulation result and measured hot water demand quantified in the previous section. As mentioned in the introduction, there are two important factors determining energy consumption, which are daily hot water use behavior of occupants and quantity of hot water accompanied by each hot water use behavior. The occupants' behavior is stochastically generated in the model, while the quantity was given by the data we are using for comparison. Thus, the validation is mainly to confirm if occupants' behavior is appropriately modelled to reproduce realistic hot water demand.

Figure 7 shows the average annual total hot water demand and its composition. The simulation result agreed well with the measured demand. Figure 8 shows the average monthly hot water demand. The model well generated seasonal variation observed in the measured demand. Figure 9 shows the average hourly hot water demand in January. The figure indicates that hot water demand between 17:00 and 22:00 was overestimated and demand between 0:00 and 2:00 was underestimated. This is due to that the behavior model allocated "Bathing and Shower" behavior mainly between 17:00 and 24:00 based on the inputted time use data while bathing behavior occurs at midnight in reality.

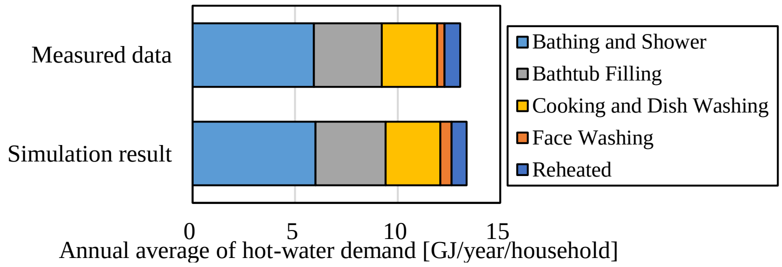

Figure 7. *Annual average of hot-water demand*

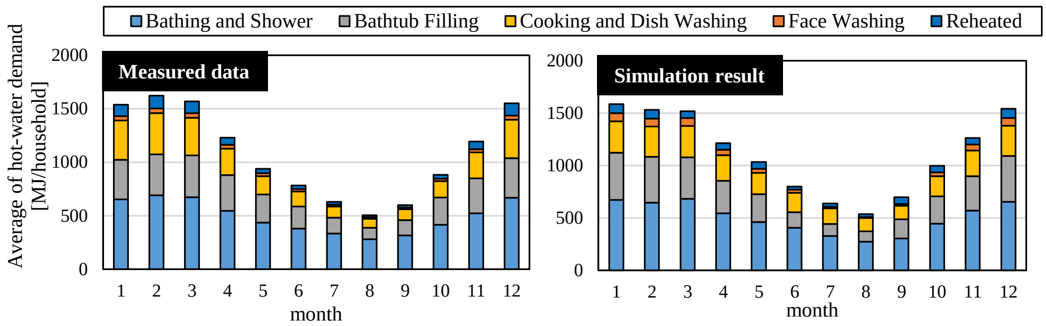

Figure 8. *Monthly average of hot-water demand*

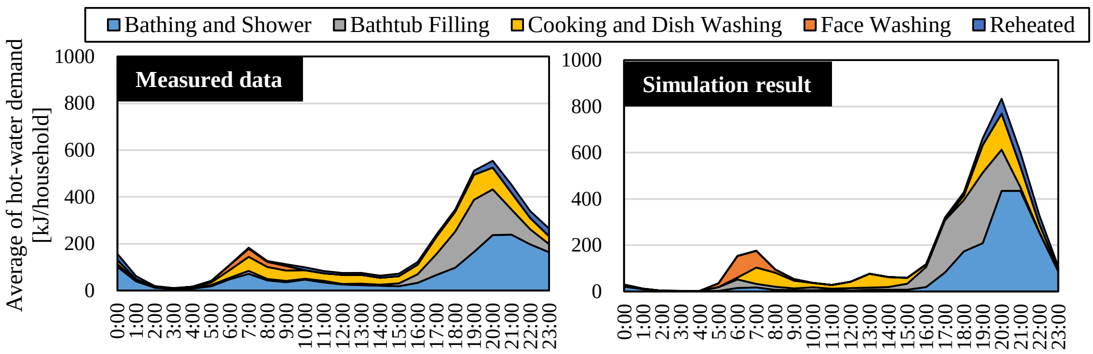

Figure 9. *Time average of hot-water demand (January)*

Figure 10 shows the frequency distribution of annual hot water demand. The amount of average hot water demand was estimated to be 13.4 GJ, agreed well with the measured data, 13.0 GJ. Standard deviation was estimated to be 3.5 GJ, which was smaller than the measured, 5.9 GJ. The underestimation of the standard deviation is attributed to the assumed frequency of hot water use behaviors and the hot water supply temperature.

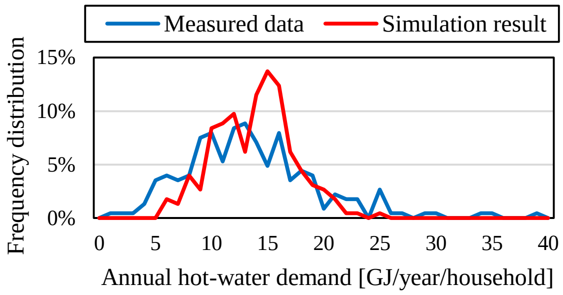

Figure 10. *Frequency distribution of annual hot-water demand*

CONCLUSION AND IMPLICATIONS

This paper presented a model estimating domestic hot water demand. The simulation model calculates daily behavior of household members and the daily behavior is converted to hot water use. The quantity of hot water accompanied with hot water use behaviors were given from a database that was developed based on measured consumption of city gas, water and electricity collected from approximately 200 households. The validation result showed that the model is capable of generating hot water demand realistically in terms of time varying feature driven by behavior of household members and the variety among households generated by the developed database on the quantity of hot water accompanied with hot water use behaviors.

REFERENCES

IBEC, http://ees.ibec.or.jp/documents/img/kaisetsu200903_06_kyuutou.pdf, last accessed on 18 August 2014.

Nabeshima, M. 1998. Statistical analysis methodology to develop building design reference, Osaka City University doctoral dissertation (JPN).

Nakahama, R., Inoue, T., Mae, M. and Hatano, R. 2009. A study on the planning and evaluation method for the new age of energy saving domestic hot water system. Part5 Actual hot water consumption in various houses, Architectural Institute of Japan, pp.889-890 (JPN).

Shimoda, Y., Okamura, T., Yamaguchi, Y., Yamaguchi, Y., and Taniguchi, A. 2010, City-level energy and CO2 reduction effect by introducing new residential water heaters, Energy 35 (2010), pp.4880-4891.

Yamaguchi, Y. and Shimoda, Y. 2014a. Validation of an Energy Demand Model of Residential Buildings, Proceedings of the 2nd Asia Conference on International Building Performance Simulation Association

Yamaguchi, Y. and Shimoda, Y. 2014b. Behavior Model of Occupants in Home based on Japanese National Time Use Survey, Proceedings of the 2nd Asia Conference on International Building Performance Simulation Association